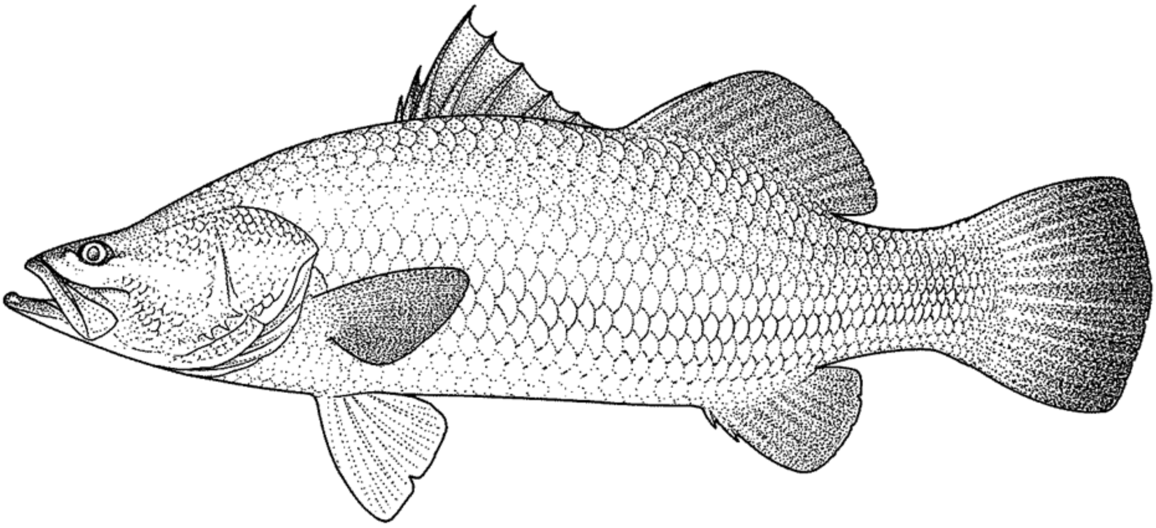
Stock assessment of the barramundi (*Lates calcarifer*) fishery in Queensland, Australia.

May 2019



THE UNIVERSITY OF QUEENSLAND
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Executive Summary

Lates calcarifer (barramundi) is a diadromous species consisting of seven genetic stocks in Queensland. All stock regions were assessed, except for the lesser fished regions of Princess Charlotte Bay and the South-East Coast, which had insufficient information. The Queensland stocks are genetically different to the stocks of the Northern Territory. Migration between stocks was not considered.

Barramundi are relatively long lived with some specimens reaching 20 to 35 years. They mature (mostly) as males first before changing into females, and move between salt and freshwater. Barramundi populations are environmentally driven, with river-flow affecting their growth, survival, and catchability.

Recent commercial catch in 2017 was around 839 tonnes in all of Queensland. With respect to the five genetic stocks considered in this assessment, the commercial catch in 2017 was 614 tonnes in the Southern Gulf of Carpentaria, 32 tonnes in the Northern Gulf of Carpentaria, 81 tonnes in the North East Coast, 55 tonnes in the Mackay, and 47 tonnes in the Central East Coast.

To assess the status of each barramundi stock, an age-structured population model with an annual time step was applied. The model data inputs included annual barramundi harvests, catch rates, age frequencies and life history characteristics.

The current stock assessment updates previous assessments by considering an age-structured model rather than a simple surplus model (as per Campbell 2007) for the five main genetic barramundi stocks. It also incorporates changes in legal size limits as well as a scenario analysis considering the effects of recreational harvest.

The model uses commercial catch data from 1988 to 2017 on the East Coast of Queensland and from 1989 to 2017 in the Gulf of Carpentaria. For scenario analyses, recreational survey data were used. For all but the Northern Gulf stock, length-and-age frequency data, collected by Fishery Monitoring (Fisheries Queensland) from commercial samples from 2000 to 2017 were incorporated in the model.

The main results of the current assessment are:

- Since 1992 there has been a general building of stock sizes relative to 1988/1989 levels.
- All stocks were estimated to be very close to or above 40 per cent exploitable biomass (relative to virgin biomass) in 2017.
- Increases in exploitable biomass (legal sized fish) were most consistent over time in the Southern Gulf, Northern Gulf, North East Coast and Central East Coast stocks. The modelled abundance of the Mackay barramundi stock has been following the same trend but decreased in recent years.
- The exploitable biomass of each stock has oscillated with periods of stability. Fluctuations were most likely a consequence of fishing pressure and cycles in floods and droughts.
- Estimates of barramundi egg production ratio, relative to assumed levels in 1988/1989, had increased for most stocks but, typically, only moderately. The egg production ratio had not markedly increased for the North East Coast and the Southern Gulf stocks.

Scenarios involving moderate cuts in Total Allowable Commercial Catch (TACC) for the Southern Gulf stock all failed to reach a biomass ratio level of 0.6 by 2027. However, a lower target of 0.5 by 2027, was achievable with total allowable catch of 468 tonnes, which corresponds to the average harvest over the past five years and is lower than 642 tonnes, which is the average harvest over the last 10 years. Projected TACCs assumed constant recruitment variation equal to that averaged over the last five years of the model (2013 to 2017). For the Southern Gulf stock, observed age-frequencies indicate that barramundi recruitment in recent years is below the long-term average, possibly because of several years of major drought in this region.

We recommend that TACCs be reviewed at least every two years (if not annually) for each barramundi stock region to allow regional management procedures to be precautionary and adaptable to the environmentally driven cycles in barramundi populations.

Genetic Stock	Estimated Biomass 2017	Estimated Egg production 2017	Average harvest (2013-2017)	Estimated Biomass 2027	Estimated Egg production 2027	Total Allowable Commercial Catch (TACC) for Biomass to equal 0.6 in 2027
	(% of original)			(% of original);TACC*5		
SGulf	0.39	0.29	468 t	0.50	0.40	≤ 468*** t
NGulf	0.73	0.61	19 t	0.81	0.68	≤ 40 t
NEC	0.53	0.25	81 t	0.63	0.38	≤ 88 t
Mack	0.59	0.43	82 t	0.57	0.39	≤ 75 t
CEC	0.71	0.50	58** t	0.73	0.52	≤ 75 t

Where biomass is the exploitable biomass of legal size fish, *5 based on a TACC using the 5-year average (2013-2017); **indicates that this value is obtained from the adjusted mean time series and does not include the Capricorn Coast Net Free Zone as these zones were outside the scope of this study; ***indicates that this attains only the lower Biomass target of 0.5.

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List of abbreviations

ECIFFF	East Coast Inshore Fin Fish Fishery
GOCIFFF	Gulf of Carpentaria Inshore Fin Fish Fishery
SGulf	Southern Gulf of Carpentaria
NGulf	Northern Gulf of Carpentaria
NEC	North East Coast
Mack	Mackay
CEC	Central East Coast
CFISH	Commercial fishing logbook database
TACC	Total Allowable Commercial Catch
MSY	Maximum Sustainable Yield
B	Exploitable biomass of legal size fish
B_0	Exploitable biomass prior to fishing i.e., virgin biomass
B_{msy}	Exploitable biomass at maximum sustainable yield
F_{msy}	Harvest rate that maximises the sustainable yield
E	Egg production
E_0	Egg production prior to fishing i.e., virgin egg production
NRIFS	National Recreational and Indigenous Fishing Survey
SWRFS	State Wide Recreational Fishing Survey
SFS	Sustainable Fisheries Strategy

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We also thank the entire Fishery Monitoring team (Fisheries Queensland), past and present, and the fishers and processors who assisted them, in obtaining and processing the length, age and other biological data, which are so critical to this stock assessment.

1. Introduction

1.1. Background

Wild-capture barramundi (*Lates calcarifer*) forms the basis of important commercial, recreational and customary Indigenous fisheries in Queensland, with an estimated combined harvest in the order of 700 tonnes in 2015 (Saunders *et al*. 2016) and more recently, 900 tonnes in 2017 (Saunders *et al*., 2018).

The development of quantitative models for barramundi (Gribble 2004; Campbell *et al.* 2008; Hall *et al.* 2008; Tanimoto *et al.* 2012; Campbell *et al*. 2017) has been challenged by the complex nature of the barramundi life-cycle (Dunstan 1959; Russell 2014), data quality issues (Campbell *et al.* 2008), and the influence of environmental factors on key biological processes and the fishery (Dunstan 1959; Davis 1982; Staunton-Smith *et al.* 2004; Robins *et al.* 2006). A further complication includes the effects of stocking barramundi fingerlings upstream that eventually contribute to the wild-caught fishery (Rimmer and Russell 1998; Wesche *et al.* 2013).

Campbell *et al*. (2008) highlighted the need for improved age, selectivity and logbook data for the barramundi fishery in Queensland. This need has been addressed to some degree with the routine collection of fish age, length and gender data by ‘Fishery Monitoring’ (Fisheries Queensland 2010) which now has an annual time series of age, length and reproductive data since 2007 (for the stocks considered in this report).

1.2. Biology

Barramundi have a complex and spatially variable life history (Russell 2014). From a stock assessment perspective, key aspects of the life history of barramundi in Queensland are:

- Longevity: barramundi are relatively long lived, with specimens of 20 years old recorded from the Gulf of Carpentaria and 35 years old recorded from the Queensland east coast.
- Protandry: most barramundi mature first as males (at two to five years), with females derived from sexually mature males at five to seven years of age (Moore 1979; Davis 1982).
- Seasonal spawning: barramundi spawn during spring and summer, with the timing and duration of the spawning dependent on water temperature, and lunar and tidal cycles.
- Non-obligatory catadromy, that is, movement between salt and freshwater: although spawned in salt water, barramundi can use numerous habitats, from fully marine to fully freshwater, during their life cycle. Supra-littoral coastal swamps act as nursery areas for juvenile barramundi. Where access permits, a variable proportion of juvenile barramundi will swim upstream to freshwater habitats, while the remainder stay in estuarine habitats. The duration and locality (i.e., distance upstream) of freshwater residency is variable between individuals, rivers and years (Halliday *et al*. 2012).
- Environmental influences: The influence of rainfall and river flow on barramundi catches has been noted for several decades (Dunstan 1959; Williams 2002; Gribble *et al*. 2005). Rainfall and seasonal flooding of rivers affect the relative recruitment of young-of-the-year barramundi (Staunton-Smith *et al.* 2004; Halliday *et al.* 2012). River-flow also affects barramundi growth rates (Sawynok 1998; Robins *et al.* 2006). Additionally, seasonal flooding allows the downstream movement of freshwater residents, thereby influencing the overall fish age-structure and length-structure of harvested barramundi, as well as changing the catchability of fish and the absolute tonnage of the commercial catch.

1.3. Stock Structure

Stock structure analysis has identified six (Keenan 1994), seven (Shaklee *et al.* 1993) or eight (Jerry *et al.* 2013) genetically distinct barramundi populations in Queensland. The current report adopts the same seven-stock structure for barramundi as Fisheries Queensland when reporting on national fish stock sustainability (Saunders *et al*., 2018). The current assessment considers the following five main stocks:

- the Southern Gulf of Carpentaria (SGulf) stock, which extends from 13° South (~ Watson River) on Western Cape York to the Queensland/Northern Territory border at ~138° East
- the Northern Gulf of Carpentaria (NGulf), 13°South on the western coast of Cape York to 11°South the northern tip of mainland Cape York
- the North East Coast (NEC) covering between 15°15’ South to 19°45’ South and 145° to 147°45’ East
- Mackay (Mack) between 19°45’ South, 147°45’ East to 22°12’ South, 150°42’ East
- Central East Coast (CEC) encompassing between 22°12’ South, 150°42’ East to 26° South, 153° East.

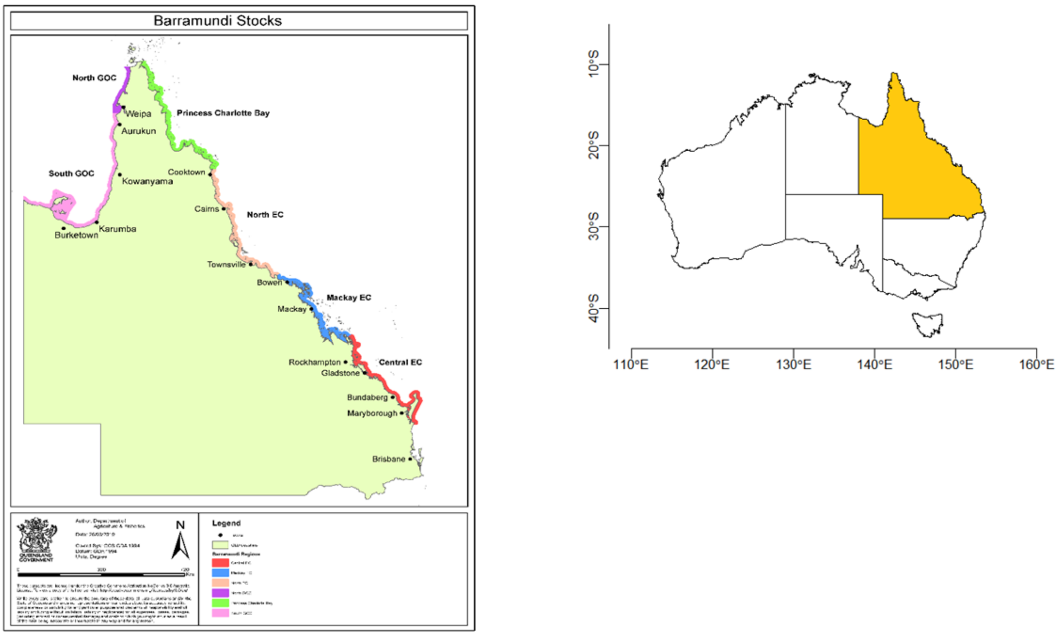


Figure 1: Geographical distribution of the barramundi genetic stock regions in Queensland.

Two stocks were not considered in the current assessment. The Princess Charlotte Bay Stock (Figure 1) has had less than 10 tonnes harvested since 2013. Previously, the commercial harvest had peaked at around 67 tonnes in 2000. The remote location and difficulties with transporting harvest out of the area currently results in limited fishing pressure on the Princess Charlotte Bay stock. The other stock not assessed was the South-East Coast stock that extends south of 26º South to the Queensland/NSW border. Although barramundi inhabit this region at low density, commercial harvest by netting is not permitted under the Queensland Fisheries Regulation 2008. As such the commercial harvest is negligible (Saunders *et al*. 2018).

1.4. Fishery

1.4.1. Commercial Harvest and Management

Barramundi are harvested as a component of two spatially separate, multi-species net fisheries that operate in estuarine and near coastal waters of Queensland. The Gulf of Carpentaria Inshore Fin Fish Fishery (GOCIFFF) extends west from 142º31’49’’ East (near Slade Point, tip of Cape York Peninsula) to the Queensland/Northern Territory border. The East Coast Inshore Fin Fish Fishery (ECIFFF) extends east of 142º31’49’’ East (near Crab Island at ~11.0º South) to the Queensland/NSW border. These fisheries are managed separately (i.e., different symbols), have different management arrangements (e.g., spawning closure dates) and complex symbol- and area-specific regulations in regards to permitted mesh-size and net-length, both per net and combined across all nets being used at any given time by a licence. For specific details, see the Queensland Fisheries Regulation 2008 (https://www.legislation.qld.gov.au/view/pdf/inforce/current/sl-2008-0083). In both fisheries, commercial catch and effort have been recorded as part of the compulsory daily logbook, referred to as CFISH since 1988/1989.

GOCIFFF and ECIFFF require a Wildlife Trade Operation (WTO) for export approval and protected species accreditation under the Commonwealth’s *Environment Protection and Biodiversity Conservation Act 1999,* to demonstrate that each fishery is operating under national sustainability guidelines.

1.4.2. Gulf of Carpentaria Inshore Fin Fish Fishery

The GOCIFFF is a multi-species fishery that includes an inshore (N3 symbol) sub-component commercial net fishery that harvests inshore species such as barramundi and king threadfin, and an offshore sub-component commercial net fishery (N12 and N13 symbols) that targets offshore species such as grey mackerel and shark (Heaven, 2018). The inshore N3 sub-component fishery uses predominately set mesh nets (i.e., gill nets, mesh size 160 to 215 mm) in rivers, creeks and nearshore waters and in offshore waters out to seven nautical miles, with a combined net length no greater than 600 m, but see https://www.legislation.qld.gov.au/view/pdf/inforce/current/sl-2008-0083 for area-specific details. The offshore (> seven nautical miles) N12/N13 sub-component fishery uses set mesh nets (mesh size 160 to 165 mm) in waters greater than seven nautical miles (from shore), with a net length of no longer than 1800 m. See Roelofs (2003) and Ward (2003) for a detailed description of the GOCIFFF, including commercial fishing methods.

In the GOCIFFF, the number of active commercial fishing boat licences (i.e., those fishers reporting catching barramundi) is variable between years. The overall trend is of declining participation (i.e., fewer fishers), with 70 active licences reporting barramundi catch in 2018. N3 symbols are attached to commercial fishing boat licences, with between one and three N3 symbols per licence. The number of N3 symbols associated with harvesting barramundi in the GOCIFFF has reduced over time, from 109 in 1998 (Queensland Government 2004) to 87 in 2008 (Queensland Government 2009) to 85 (as of 15 January 2019, Fisheries Queensland licensing database).

1.4.3. East Coast Inshore Fin Fish Fishery

The ECIFFF is Queensland’s largest and most diverse fishery that includes an inshore commercial net fishery sub-component that harvests inshore species such as barramundi and king threadfin (N2 symbol) and an offshore commercial net fishery sub-component that targets offshore species such as grey mackerel and shark (N1, N4 (>20 m depth), eastern N11 and S symbols). The inshore N2 sub-component of the ECIFFF uses predominately set mesh nets (i.e., gill nets) in rivers, creeks and nearshore waters.

In the ECIFFF, the number of active commercial fishing boat licences (i.e., those fishers reporting catching barramundi) is variable between years. For a number of reasons, the overall trend is of declining numbers of active licences (i.e., fewer fishers), with 94 active licences reporting barramundi catch in ECIFFF in 2018. Reduction in licence numbers is due (in part) to licence buybacks within ECIFFF, spatial closures (introduced in 2004) associated with the Great Barrier Reef Marine Park Representative Areas program and more recently, on 1 November 2015, the introduction of net-free fishing zones (where commercial net fishing is excluded) in Cairns, Mackay and Capricorn Coast. The number of N2 symbols associated with licences harvesting barramundi in the ECIFFF have reduced over time, from 271 in 1997 (DEEDI 2001) to 94 (as at 15 January 2019, Fisheries Queensland licensing database).

1.4.4. Recreational and Indigenous Harvest

Barramundi is a key target species for recreational anglers in Queensland, taken by line fishing in freshwater, estuarine and marine waters. Effort within the recreational fishery is not limited or licensed, although the management arrangements of minimum and maximum size limits, seasonal (spawning) closures and an in-possession limit of five apply to recreational fishers.

The scale of Queensland recreational fishing for barramundi (effort, catch, release and harvest) is estimated through telephone-diary survey methods (Webley *et al.* 2015). The 2013 to 2014 recreational fishing survey estimated that 174000 barramundi were caught across Queensland, of which 132000 were released after capture and 42000 were retained for harvest (Webley *et al.* 2015); noting that these estimates have moderate standard errors and should be used with caution. Possession limits and size limits were the major reasons for the high release rate (i.e., 76 per cent) of captured barramundi. Based on an average individual fish weight of 4.21 kg, Webley *et al.* (2015) estimated a recreational harvest weight of barramundi for Queensland-based fishers of 131 tonnes compared to a total commercial harvest across Queensland in 2014 of 762 tonnes.

Recreational fishing catch data were not used in the current stock assessment, due to an insufficient temporal record and the necessity for assumptions on post-release survival. However, a scenario analysis with the incorporation of two different estimates of recreational harvest, has been considered. The details are discussed in Section 3.6 and Section 4.

1.4.5. Management

Barramundi has a long history of fisheries management in Queensland with numerous changes to management arrangements for inshore net fisheries (see Appendix A).

Key current management arrangements within the GOCIFFF for the N3 sub-component that are relevant to barramundi include (Queensland Fisheries Regulation 2008):

- a minimum size limit of 580 mm
- a maximum size limit of 1200 mm
- a seasonal (spawning) closure preventing the harvest of barramundi and all commercial net-fishing between midday 7 October and midday 1 February of each year
- limited number of commercial net fishing symbols: 85 N3 symbols in 2018

- mesh size limitations: 160 mm to 215 mm for rivers, creeks and nearshore waters; 160 mm to 165 mm for offshore waters (to seven nautical miles)
- net length limitations per active licence: a combined net length not longer than 360 m in rivers and creeks; and a combined net length not longer than 600 m in nearshore waters; a combined net length not longer than either 300 m (one N3 symbol on a licence) or 600 m (more than one N3 symbol on a licence) in offshore waters
- legislated net attendance rules while fishing
- spatial closures to commercial and recreational fishing

Key current management arrangements within ECIFFF for the N2 symbol sub-component that are relevant to barramundi include (Queensland Fisheries Regulation 2008):

- a minimum size limit of 580 mm
- a maximum size limit of 1200 mm
- a seasonal (spawning) closure preventing the harvest of barramundi and all commercial river set-net fishing between 1 November and 1 February
- limited number of commercial net fishing symbols: 94 N2 symbols in 2018
- mesh size limitations: 150 mm to 215 mm for rivers and creeks (Kauri Creek to Cape Flattery); 100 mm to 215 mm for nearshore waters (Baffle Creek to Cape Flattery).
- net length limitations per active licence: a combined net length not longer than 360 m in rivers and creeks; and a combined net length not longer than 600 m in nearshore waters.
- legislated net attendance rules while fishing
- spatial closures to commercial net-fishing including:
    - dugong protection areas (DPA's, http://www.gbrmpa.gov.au/access-and-use/special-management-areas)
    - Net-free zones – Trinity Bay (Cairns), St Helens Beach to Cape Hillsborough (Mackay), Capricorn coast (Keppel Bay to Fitzroy River) (https://www.business.qld.gov.au/industries/farms-fishing-forestry/fisheries/net-free-zones)
    - Other regulated waters see https://www.legislation.qld.gov.au/view/pdf/inforce/current/sl-2008-0083

Of the listed management arrangement over time, key changes, such as changes to the minimum size limit and introduction of the maximum size limit have been incorporated into the current stock assessment.

1.5. Stocking

Barramundi is a species that is reared in hatcheries and then stocked in considerable numbers as fingerlings, into many impounded waterways throughout Queensland. The escape of these fish during floods is a complication for the assessment and management of barramundi stocks, due to the uncertain contribution these fish make to the wild estuarine populations. Some combinations of stocking practices and flood events have led to major impacts on the total barramundi catch and Fishery Monitoring data on the Queensland east coast (Wesche *et al.,* 2013). Information on stocked barramundi in Queensland is collated in Appendix B.

2. Source Data and Standardisation

2.1. Commercial Catch

The current stock assessment model is driven by catch and fitted to a standardised catch. Commercial catch and effort data for barramundi were extracted from the Fisheries Queensland CFISH logbook database (DR2530). For the Gulf of Carpentaria, the recorded 1988 data have a low number of data entries and is inconsistent with the expected harvest from the fishery. Thus, we consider the logbook data from 1989 onwards for Gulf stocks. Consequently, Figure 2 displays the annual catch of barramundi from 1989 to 2017 for Gulf stocks (Southern Gulf and Northern Gulf) and 1988 to 2017 for East Coast stocks (NEC, Mackay and CEC).

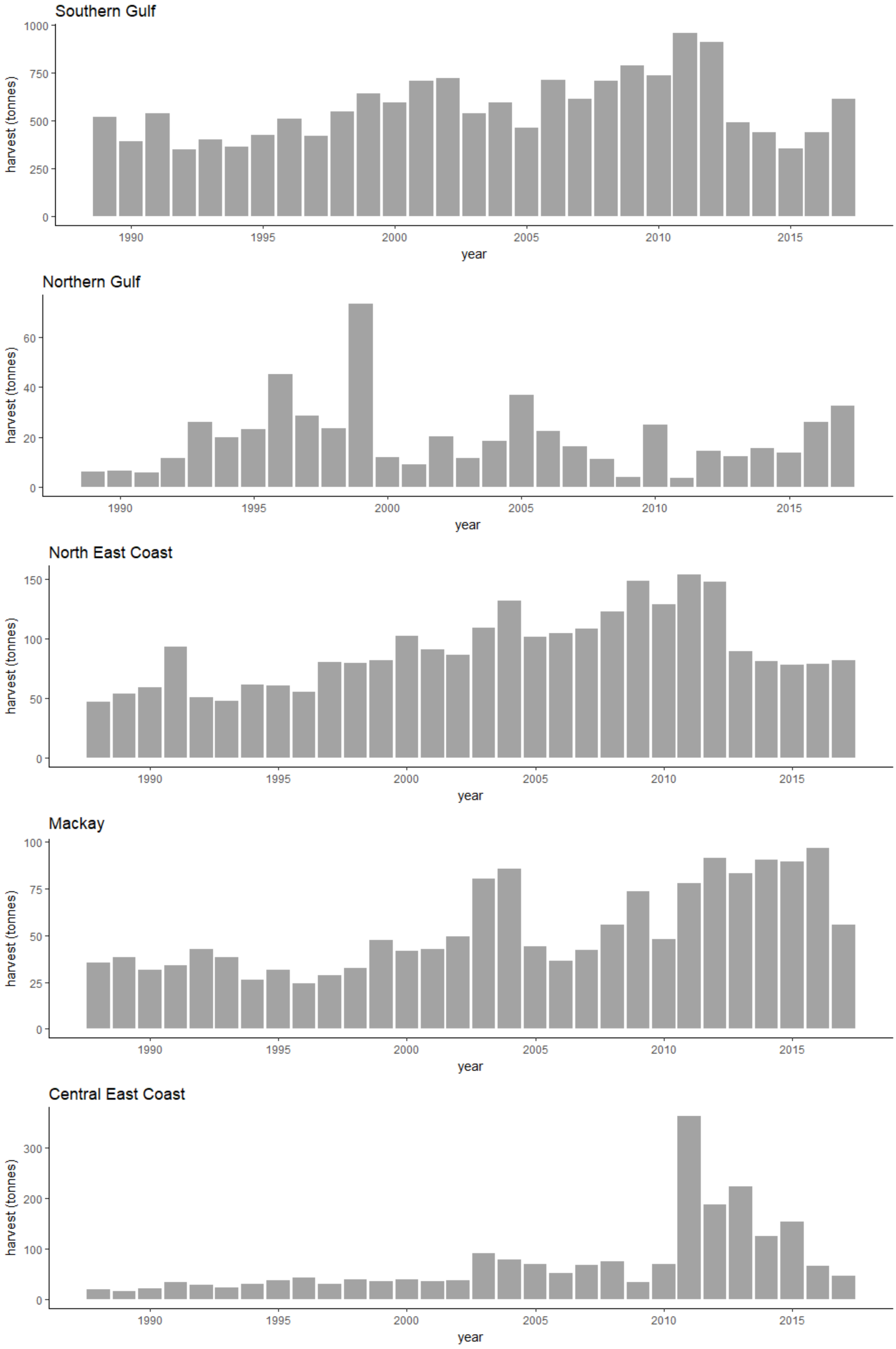


Figure 2: Annual commercial catch of barramundi from 1989 to 2017 for Gulf stocks (Southern Gulf and Northern Gulf) and 1988 to 2017 for East Coast stocks (North East Coast, Mackay and Central East Coast).

2.2. Standardisation of catch and effort data

Catch and effort data, obtained from Queensland’s compulsory CFISH logbook database, were analysed to provide a measure of abundance for legal-sized barramundi for each stock in each year, by means of a standardised catch rate.

The standardisation accounts for the effort, measured in the number of days fished. A more precise measure would have been the effort hours but those were not commonly reported prior to 2006 and would require further assumptions. A continuous periodic function was used to capture the differences in catchability throughout the year given the different seasons and tidal effects. Although the length of gillnets affect the catchability, it does so in a nonlinear way as a longer net does not necessarily imply a larger catch. For that reason, we grouped the logbook entries into four net-length ranges: <180 m, 180-260 m, 260-400 and >400 m. As an approximation for skill level, the authority chain number (≅ an anonymous identifier for commercial fishing operation) was used. Variations in catchability based on the 30 by 30 minute grid (i.e., CFISH grid) were assumed to be normally distributed within each degree of latitude. The method is described further in Appendix C.

The Southern Gulf, Northern Gulf, North East Coast, Mackay and Central East Coast stocks show an overall increasing trend in the catch rate, albeit with some between year fluctuations (Figure 3). All stocks have a substantial increase in standardised catch rates from 2010 onwards for two or three years, depending on stock that is probably a consequence of flood events throughout Queensland in these years. The Central East Coast stock has a dramatic increase in catch (Figure 2) and standardised catch rate (Figure 3) from 2011 onwards. This was caused by 2010/11 flood events, most significantly overflowing of the Awoonga Dam on the Boyne River. During this event, an estimated 30000 large (i.e., estimated as 800 mm average total length) barramundi previously stocked into Awoonga Dam escaped over the dam spillway, and became (over time) available to the commercial (and recreational) fishery (Wesche *et al.* 2013). Thus, the biomass of barramundi available to the commercial fishery increased due to stocked fish rather than due to natural population dynamics. We have tried to account for these stocked fish and their effect on standardised catch rates for the Central East Coast stock so that the modelled biomass was not overestimated, see details in Section 4.5.

The standardised catch rates for the Mackay stock shows a long-term increase. This could be caused by an expansion of the fishery as indicated by an increase in the median number of fishing days per year recorded for each authority chain number. However, the total number of active authority chain numbers does not increase over the recent years. Put simply, the number of active fishing operations (licences/boats) is stable over time, but the number of days fished (i.e., median days fishers fished) has increased.

The standardised catch rates for the Northern Gulf stock have large variance especially in 2009 and 2011 (Figure 3). This variability comes from the low number of fishing records (i.e., in some years less than two authority chain numbers).

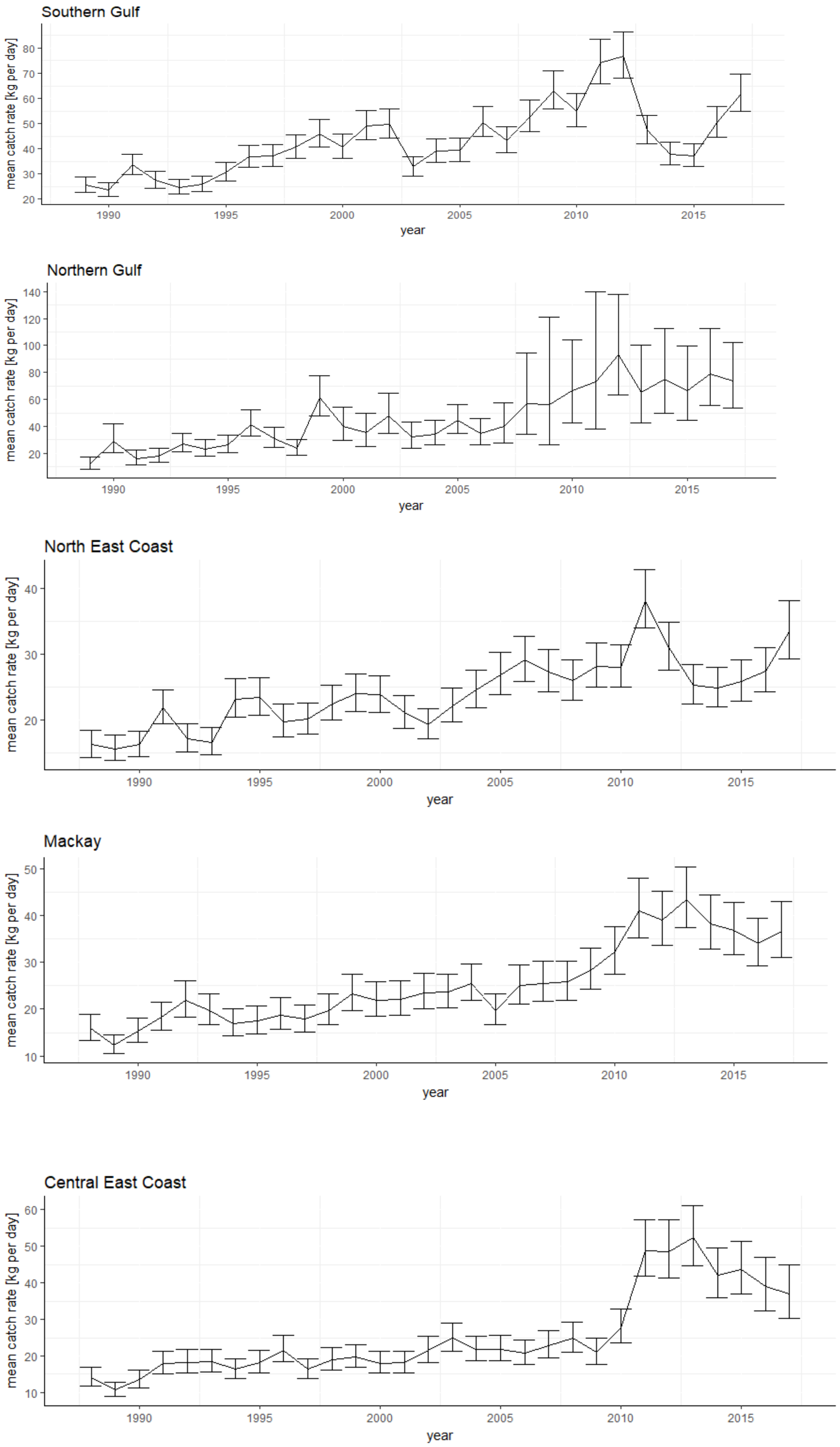


Figure 3: Mean annual standardised commercial catch rates (kg per day fished) based on recorded CFISH logbook data.

2.3. Length and age data

Length- and age-frequency data, collected by Fishery Monitoring (Fisheries Queensland) from commercial samples from 2000 to 2017 in the Southern Gulf and 2007 to 2017 in the North East Coast and 2007 to 2010 Central East Coast (Fisheries Queensland 2010) were used in the current assessment.

The length information represented total length measured from 25953 barramundi in the Southern Gulf stock, 22611 barramundi in the North East Coast stock and 12710 barramundi in the Central East Coast stock.

Age-class was determined from visual assessment of increment counts and edge interpretation of thin-sectioned otoliths and an age-allocation matrix (Fisheries Queensland In Prep.) for 9398 barramundi from the Southern Gulf stock, 9367 barramundi from the North East Coast stock and 7038 barramundi from the Central East Coast stock.

The Fishery Monitoring program does not collect length and age data of barramundi for the Northern Gulf or Mackay stocks. Therefore, in the absence of such data, age-frequency of the North East Coast and Mackay stock were assumed to be similar (see Section 3.4). Due to expected differences in the age relationship between the Northern Gulf and its adjacent neighbour the Southern Gulf stock (Davis 1984a), no age-frequency data were used in model fitting for the Northern Gulf stock (see Section 3.4).

Annual age-frequencies were supplied by Fisheries Queensland and represented the adjusted age-frequency accounting for variation in annual length-at-age (age-length key for 20 mm length classes) spatial catch sampling and commercial catch region (Fisheries Queensland 2010).

The volatility of the barramundi stock in the Southern Gulf is noticeable in Figure 4. Instead of observing a relatively constant contribution of different age-class proportions, the age-frequency data in the Southern Gulf stock shows change in age-class proportions over time. These large variations are most likely caused by environmental factors affecting the survival of juvenile barramundi. Up to 2012, the Southern Gulf fishery was based on young fish (age-classes three and four), while the fishery in 2016 and 2017 was based on older fish (age-classes five and six). This manifests itself in the decrease in the proportion of young fish (i.e., three-year-olds) over the decade for which age-frequency data had been collected in the Southern Gulf stock (see Figure 4). The reduced proportion of three-year-old fish, which is apparent since 2015, could imply a reduced egg production and/or reduced survival of juveniles (zero- to two-year-olds) in the preceding years. This is notable because the egg production is a measure of the sustainability of a stock.

The trends displayed in Figure 3 and Figure 4 point to what could be an important feature. On the one hand the standardised catch rates increase, implying a positive trend for the overall abundance. On the other hand, the reduced number of young fish implies a declining egg production ratio and/or survival of juveniles.

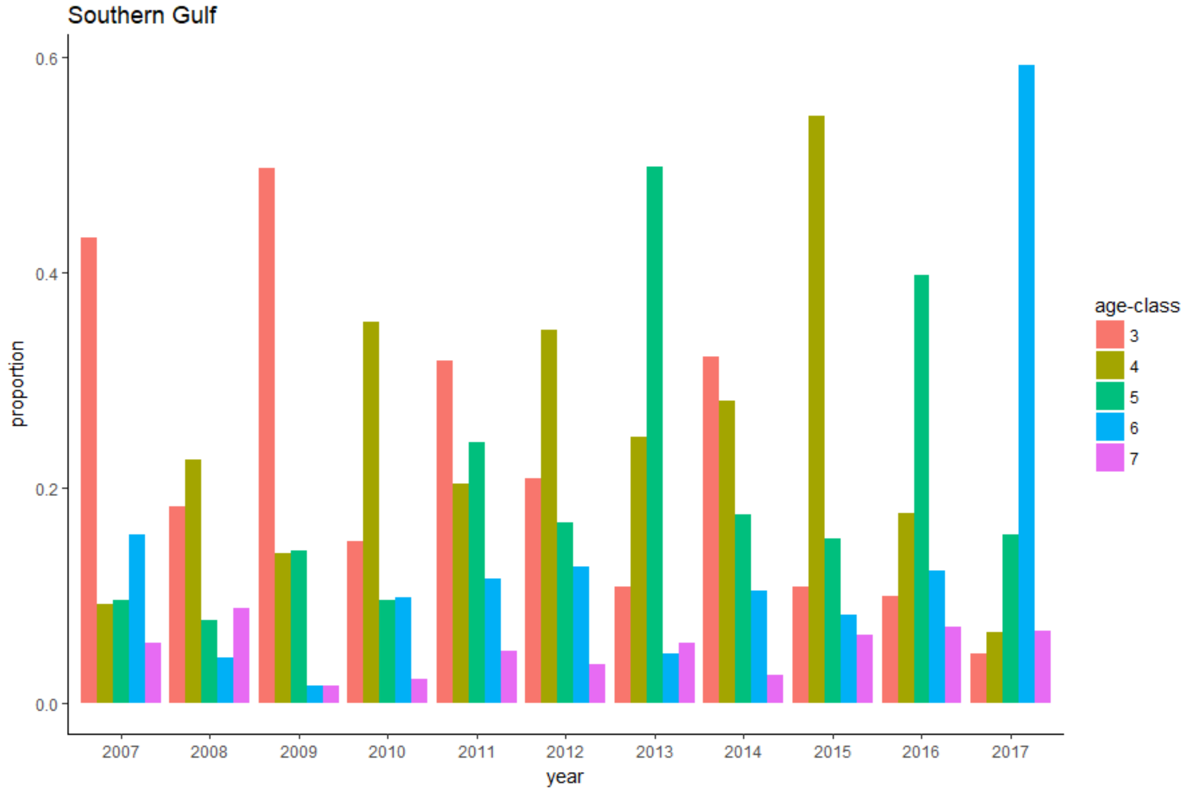


Figure 4: Southern Gulf barramundi stock proportion age-frequency for age-classes three to seven based on data collected by the Fisheries Queensland Fishery Monitoring program between 2007 and 2017.

Another possible reason for the apparent reduction in the proportion of three year-old fish in 2016 and 2017, could be the presence of slow growing juveniles. Barramundi growth can be related to environmental drivers, such as river flow (Robins *et al.* 2006). If juveniles are growing more slowly, they will not reach the length to be commercially sampled by age three. Since the data stem from samples of commercially harvested fish, they inherit this length-bias. However, the growth variability (possibly environmentally driven) through time is not explicitly included in the current model structure and stock assessment.

A similar phenomenon can be observed in the North East Coast stock (Figure 5) where the proportions of fish born in 2013 and 2012 (i.e., age-classes three and four in 2016) are reduced compared to earlier years.

The Central East Coast stock shows a decline in proportion of three-year-old fish since 2013 (Figure 6). However, the years 2011 to 2013 contain effects from the flooding where stocked fish contributed to commercial catch. Given the flooding and its effects, it is difficult to disentangle the consequences of the flooding to the age-length data and therefore correctly interpret the proportion age-frequency over time for this stock.

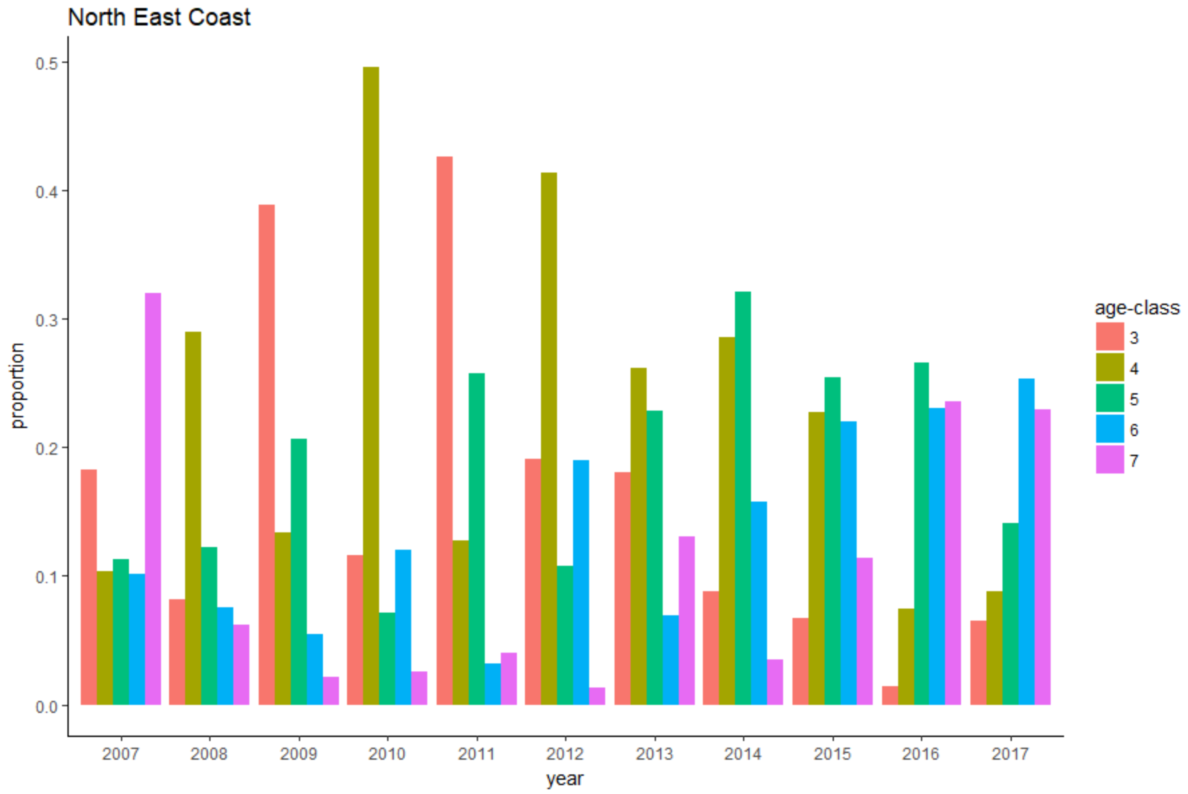


Figure 5: North East Coast barramundi stock proportion age-frequency for age-classes three to seven based on data collected by the Fisheries Queensland Fishery Monitoring program between 2007 and 2017.

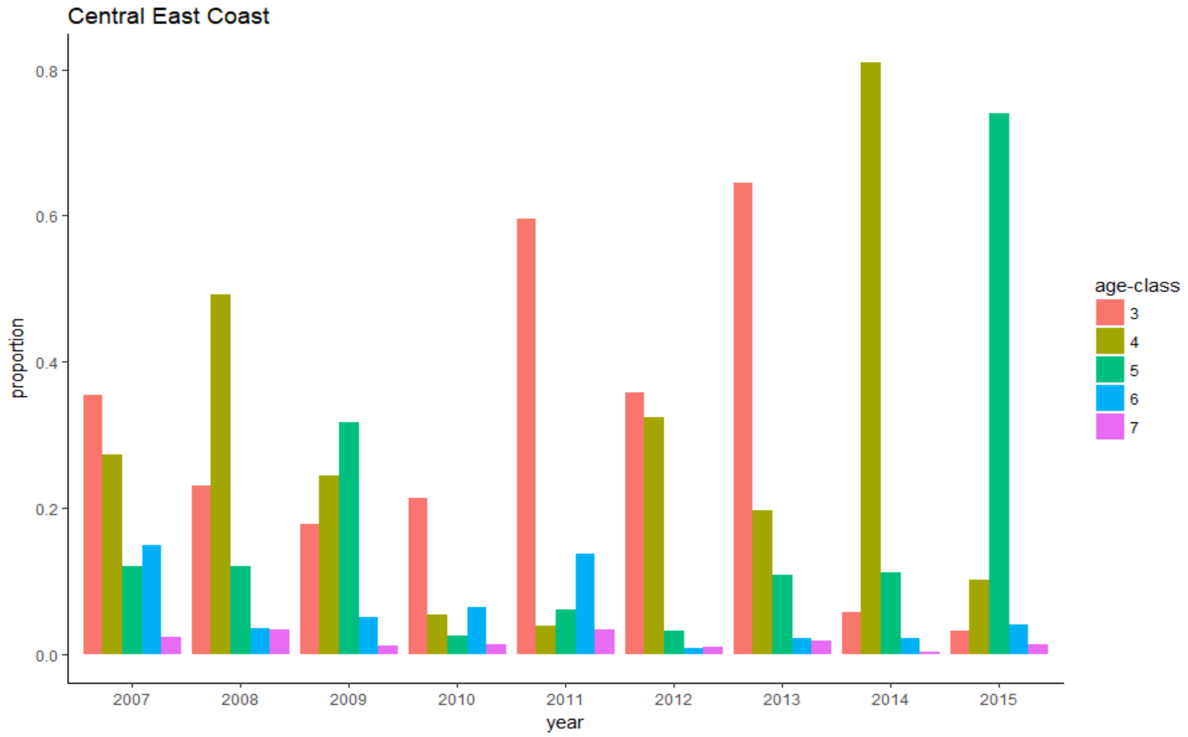


Figure 6: Central East Coast barramundi stock proportion age-frequency for age-classes three to seven based on data collected by the Fisheries Queensland Fishery Monitoring program between 2007 and 2015.

3. Technical Model Description

This section details the mathematical structure of the underlying scientific model, its calibration, assumptions and limitations. Figure 7 shows logical relationships among functions explained and their roles in barramundi population dynamics. The blue shapes in Figure 7 list some of the main functions used in the population model, which itself is highlighted in green. The yellow rectangles represent the data that were used. The “Harvest” data box is placed on the left because it is used within the dynamics of the model, while the standardised catch rate and the age-length data are on the right because they are used in the statistical fitting of the model parameters.

The current population model contains several features that had not been incorporated in previous barramundi stock assessments. These include,

- The first age-structured model for the North East Coast stock
- Incorporation of variability in the length-at-age relationship
- Incorporation of all changes in legal size limits in the selectivity
- Estimation of stock specific female-at-length proportion based on observed data (i.e., Fishery Monitoring data).

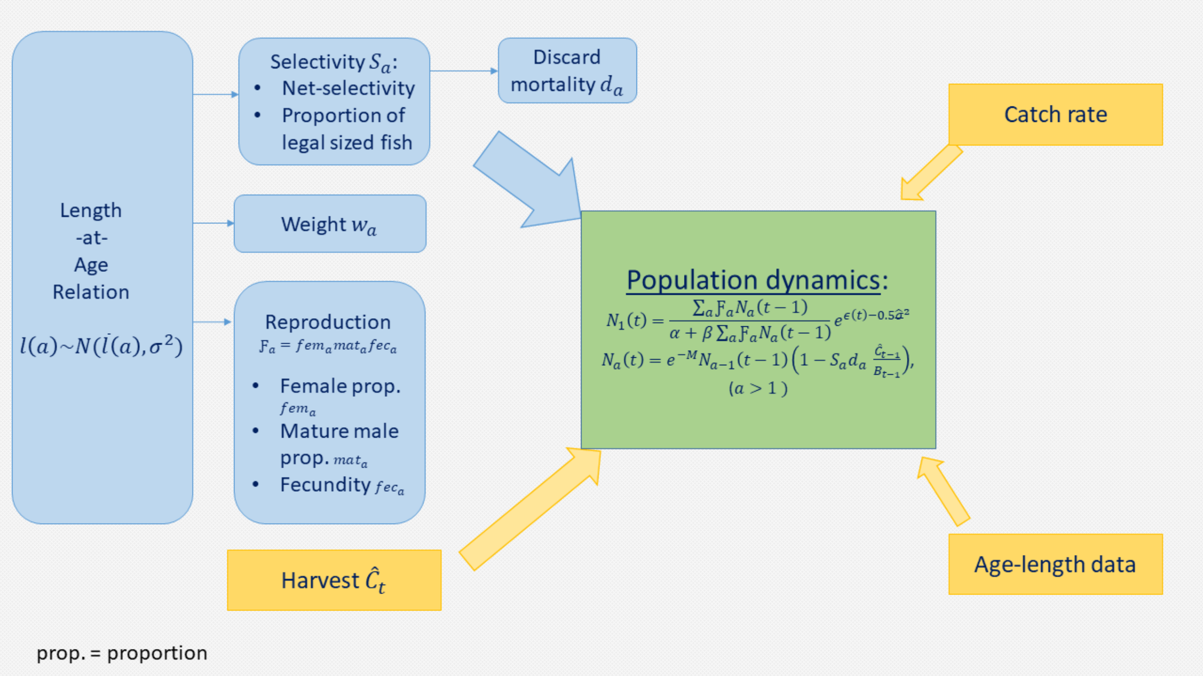


Figure 7: Flow chart of the barramundi population model and data inputs.

3.1. Selectivity over time

Selectivity was primarily based on the field study by Hyland (2007), who set gill nets of various mesh sizes in Princess Charlotte Bay and Trinity Inlet. The selectivity estimation approach followed Sparre *et al.* (1989) with statistical analysis based on Millar and Holst (1997) and Millar and Fryer (1999).

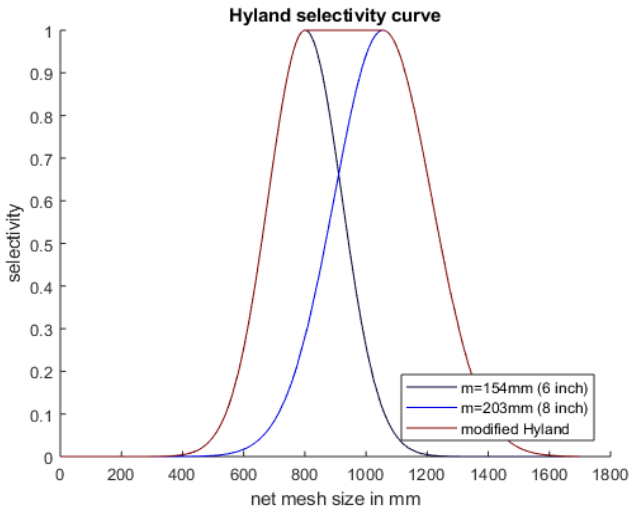


Figure 8: Selectivity curve modified from Hyland (2007) based on reported minimum and maximum mesh sizes.

Hyland (2007) produced a three-parameter selectivity curve to determine the selectivity $sel(l)$, at length l as

$$sel(l) = \exp\left\{-\frac{(l-k_1 m)^2}{2k_2 m^2}\right\},$$

where m is the mesh size in mm, k_1, k_2 are parameters fitted to experimental data ($k_1 = 5.2, k_2 = 0.619$).

In years where more than one mesh size was reported in the commercial logbook data, a modified Hyland curve was derived (red curve in Figure 8).

The net selectivity was then given by

$$sel(l) = \begin{cases} \exp\left\{-\frac{(l-k_1 m_{min})^2}{2k_2 m_{min}^2}\right\}, & l < k_1 m_{min} \\ 1, & k_1 m_{min} \le l \le k_1 m_{max} \\ \exp\left\{-\frac{(l-k_1 m_{max})^2}{2k_2 m_{max}^2}\right\}, & l > k_1 m_{max} \end{cases}$$

The modified Hyland curve assumes full selectivity for length-classes selected between the minimum mesh size and the maximum mesh size recorded during days fished in the CFISH logbook database, see red curve in Figure 8.

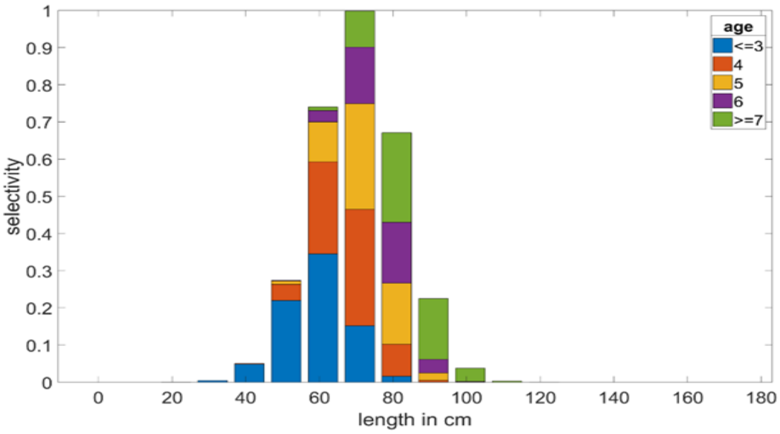
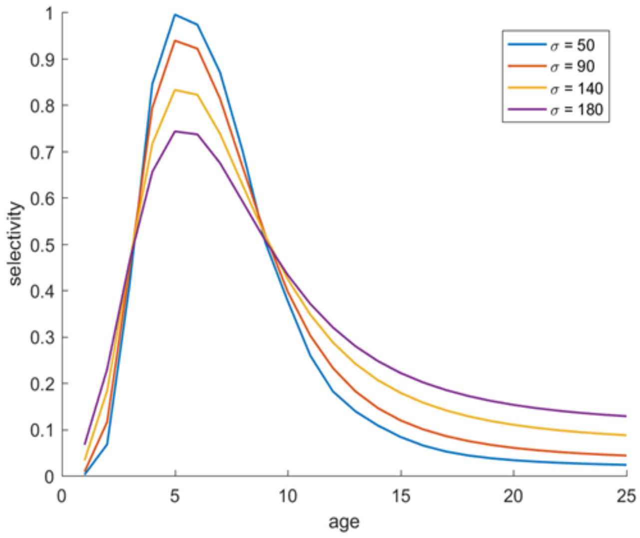


Figure 9: Selectivity-at-length curve, distributed across age-classes using L_∞ = 1300 mm, k = 0.17, a_0 =-0.47, σ = 113 (median values of the fitted von Bertalanffy curve for the Southern Gulf stock).

Assuming that the length-at-age is normal distributed, explained in more detail in Section 3.3, the selectivity-at-length is distributed across age-classes as illustrated in Figure 9.



It should be noted, that the selectivity-at-age curve depends on the age-at-length relationship and therefore on the von Bertalanffy parameters and the variance σ^2 of the length-at-age distribution.

Figure 10 visualises the selectivity for different age-classes for different variance σ^2. The plot shows that with increasing variance σ^2 in the length-at-age relationship, the wider the transformed selectivity-at-age curve. The dome shaped selectivity-at-length curve carries over to the selectivity-at-age curve.

Figure 10: Selectivity-at-age for different variances (σ) of the length-at-age distribution using L_∞ = 1300 mm, k = 0.17, a_0 =-0.47 for the Southern Gulf stock.

Based on the CFISH logbook database, the mesh sizes that resulted in the majority of the annual total reported barramundi catch were used in the population model. A mesh size of six inch (154 mm) dominated the commercial catch and effort in the Southern and Northern Gulf stocks for the years 1988 to 1996, before a (fisher instigated) regulated change to the minimum mesh size to 6.5 inch (165 mm, see Appendix A) resulted in most of the commercial catch in the Gulf taken by 6.5 inch mesh (Figure 11). For stocks on the Queensland east coast, a variety of mesh sizes were reported. In these cases, the minimum and maximum mesh size were determined. In the North East Coast, the minimum net mesh-size of six inch and a maximum of seven inch (177.8 mm) were used in the modified Hyland selectivity curve (Figure 8). In the Mackay and Central East Coast stocks, the range was six to eight inch (203 mm), see Figure 12.

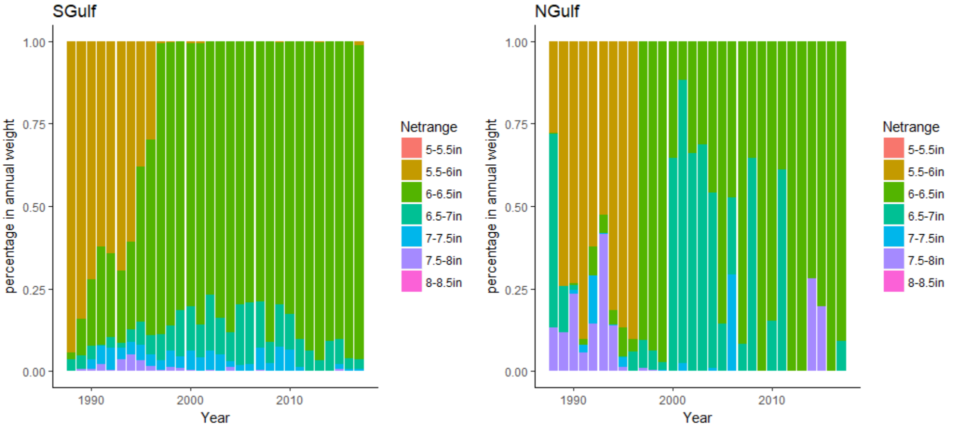


Figure 11: Per cent (by weight) of annual barramundi commercial catch by gill-net mesh size (in inches) reported in the CFISH logbook database for the each stock in the Gulf of Carpentaria.

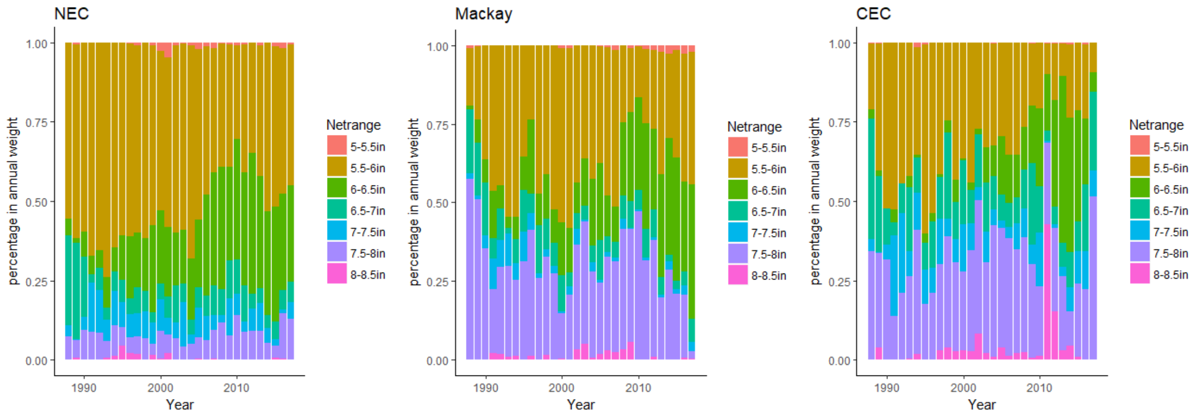


Figure 12: Per cent (by weight) of annual barramundi commercial catch by gill-net mesh size (in inches) reported in the CFISH logbook database for each stock on the Queensland east coast.

3.2. Fecundity, maturity and proportion of females

Female fecundity and male maturity are based on results of Davis (19824b) and Davis (1982) respectively. Davis (1984b) found an exponential relationship between length (measured in mm) and fecundity (measured in number of eggs produced), namely

$$fec(l) = \eta exp(\xi l)10^6,$$

where $\eta = 0.3089$ and $\xi = 0.0035$.

Davis further suggests the following relationship between the proportion of mature barramundi males and their length (measured in mm)

$$mat(l) = \frac{1}{1 + e^{\eta - \xi l}}$$

This relationship was fitted to data provided in Table 1 of Davis (1982) “Percentage at each maturity state in the Gulf of Carpentaria”. The fitted values were $\eta = 13.187, \xi = 0.0207$, see Figure 13.

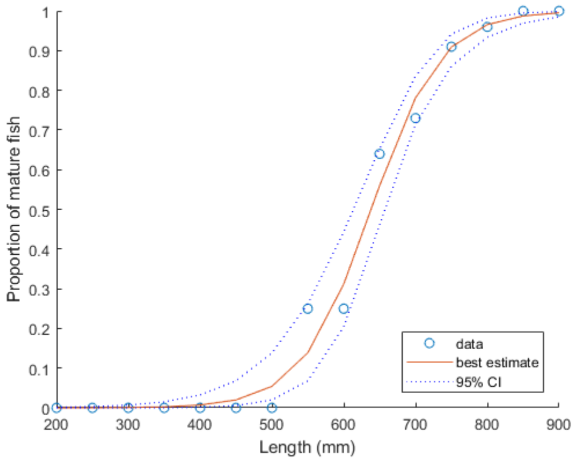


Figure 13: Male maturity-at-length relationship for Gulf of Carpentaria barramundi fitted to data in Table 1 of Davis (1982).

The Fishery Monitoring program for barramundi has sampled over 14763 barramundi (of which 3892 were female) across Queensland for sex (determined by macroscopic assessment) and length between 2000 and 2018. The current assessment used the same approach as Davis (1982) to fit a function for the proportion of female-at-length i.e.,

$$fem(l) = \frac{1}{1 + e^{\eta - \xi l}}.$$

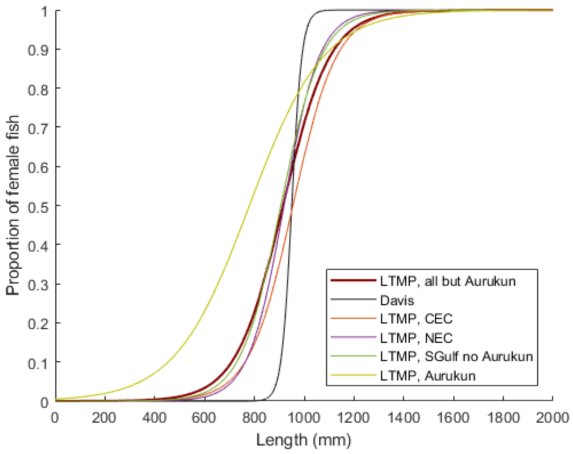


Figure 14: Fitted logistic function of the proportion of female-at-length for Queensland barramundi.

Preliminary analyses of proportion female-at-length by stock by 'sampling region' (Fisheries Queensland 2010) suggested that most sampling regions had curves that were similar, but that the Aurukun sampling region was different (Robins, Whybird and Budd unpublished data). This may be suggestive of precocious maturity for fish north of the Archer River, as noted by Davis (1984a).

Since all Fishery Monitoring regions, except Aurukun, provided a similar fit, only one curve was fitted to these regions representing the relationship between the proportion of female barramundi and their length (in mm) for the Southern Gulf and Queensland east coast stocks. The estimated parameters were $\eta = 9.3034, \xi = 0.021$.

For the Northern Gulf stock, the functional equation was fitted to the Aurukun data (13˚S to 14˚S), see Davis (1985). In this case, the values η and ξ were estimated to be $\eta = 5.247, \xi = 0.006727$.

Given a specific length-at-age distribution, the different age-classes can be estimated within length groups. Fish ≥ 10 years old dominate length-classes ≥1000 mm (Figure 15). This is also where the proportion of females in any length-class is ≥ 0.8, given that most barramundi mature initially as males then change sex to become female. Since the length-at-age relationship considers differences in the growth, a fish of five years could have already obtained a length of 800 mm and could be a female. As before, the precise distribution of these age-classes per length depends on the von Bertalanffy parameters and the variance in the age-at-length distribution. Note that is also possible for smaller and younger fish to be female.

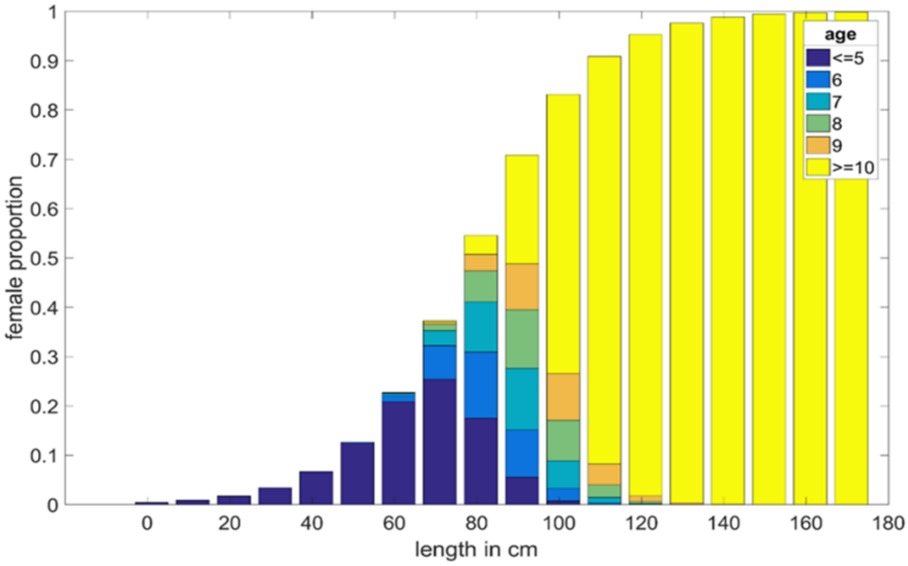


Figure 15: Female proportion-at-length for Queensland barramundi indicating the estimated age-distribution within each length-class.

3.3. Population Dynamics

The current model is a traditional age-structured population model with an annual time step and biomass measured in tonnes. The population dynamics input is total annual catch and fitted to standardised annual catch rates and age-frequency data, if available.

The number of barramundi at age $a + 1$ at time $t + 1$ is described by

$$N_{a+1}(t+1) = \begin{cases} N_a(t)e^{-M}\big(1 - sel_a d_a U(t)\big), & a = 1, \dots, 24 = a_{max-1} \\ \dfrac{E(t)}{\alpha + \beta E(t)} \exp(\epsilon(t) - 0.5\,\hat{\sigma}^2), & a = 0 \end{cases}$$

where t is the year, a denotes age of the fish in years, $a_{\max}$ is the oldest modelled age (here 25), M is the annual instantaneous natural mortality rate (fixed at 0.28), sel_a is the net-selectivity-at-age a, d_a is the discard mortality at age a, $U(t) = \frac{\hat{C}(t)}{B(t)}$ represents the harvest rate at time t, where $\hat{C}$ is the recorded total annual catch (in tonnes) and $B(t)$ is the exploitable biomass at time t (in tonnes). In order to account for annual variations in the recruitment, the factor of $\exp(\epsilon(t) - 0.5\,\hat{\sigma}^2)$ was added to the Beverton-Holt recruitment, see Shirripa *et al*. (2009).

Length-at-age $l(a)$ was assumed to follow a normal distribution $N(\mu, \sigma^2)$ with the mean given by the von Bertalanffy curve $\mu = \overline{l(a)} = l_\infty(1 - \exp\{-k(a - a_0)\})$. This allowed us to transform length related function $f(l)$ into an age related function $\hat{f}_a$ via

$$\hat{f}_a = \textstyle\sum_l p(l|a) f(l),$$

where $p(l|a) = l(a) \sim N(\overline{l(a)}, \sigma^2)$.

Net-selectivity-at-length $sel(l)$ was given by the modified Hyland curve. More precisely

$$sel(l) = \begin{cases} \exp\left\{-\dfrac{(l - k_1 m_{min})^2)}{2k_2 m_{min}^2}\right\}, & if\ l < k_1 m_{min} \\ 1, & if\ \ k_1 m_{min} \le l \le k_1 m_{max}, \\ \exp\left\{-\dfrac{(l - k_1 m_{max})^2)}{2k_2 m_{max}^2}\right\}, & if\ l > k_1 m_{max} \end{cases}$$

where $k_1 = 5.2,\ k_2 = 0.619$ and m_{min}, m_{max} are the minimum and maximum mesh sizes used in a stock. In order to obtain net-selectivity-at-age sel_a, we follow the above described method, namely

$$sel_a = \sum_l p(l|a) sel(l).$$

While $\mathrm{sel}(l)$ considers the net-selectivity, the selectivity S takes also legal size limits into account, using

$$S_a = r_a^{\mathrm{legal}} sel_a,$$

where r_a^{legal} is the ratio of fish-at-age a that are within the legal-size limits.

The legal size limits of barramundi have changed over time (see Appendix A and Figure 16). The current assessment incorporated the following size limits for the respective periods:

- minimum legal size 1955 to 1988 of 508 mm (all stocks)
- minimum legal size 1989 to 1991 of 550 mm (all stocks)
- maximum legal size 1992 to 2017 of 1200 mm (all stocks)
- minimum legal size 1992 to 2017 of 580 mm (east coast)
- minimum legal size 1992 to 2011 of 600 mm, and 2012 to 2017 of 580 mm Southern and Northern Gulf stocks

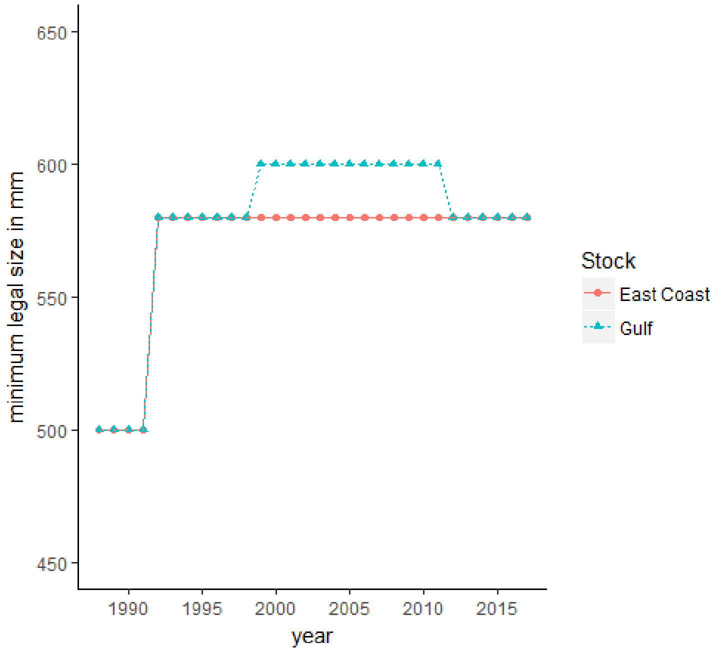


Figure 16: Minimum legal size regulations for Queensland barramundi, 1988 to 2017.

The ratio r_a was obtained by using the length-at-age relationship $l(a) \sim N(\overline{l(a)}, \sigma^2)$ in the following way

$$r_a^{\text{legal}} = \frac{\sum_{l \geq l_{min}}^{l \leq l_{max}} p(l|a)}{\sum_l p(l|a)},$$

where l_{min}, l_{max} are the minimum and maximum legal sizes.

The ratio was further used to obtain the discard mortality by

$$d_a = r_a^{\text{legal}} + 0.1\left(1 - r_a^{\text{legal}}\right).$$

This assumed a discard mortality of 10 per cent for fish below the minimum legal size (Grace *et al.,* 2008) and a discard mortality of 10 per cent for fish above the maximum legal size (I. Halliday, unpublished; Tanimoto *et al.,* 2012).

The exploitable biomass at time t was therefore given by

$$B(t) = \sum_a w_a S_a N_a(t),$$

where weight-at-age was derived by weight-at-length using

$$w_a = \sum_{l\geq l_{min}}^{l_{max}} p(l|a)w(l) = w_1 \sum_{l\geq l_{min}}^{l_{max}} p(l|a)l^{w_2},$$

with $w_1 = 1.1 \cdot 10^{-5}, w_2 = 3.02$ (l measured in mm, w measured in g), see Tanimoto *et al*. (2012).

Reproduction was given by the Beverton-Holt equation with the egg production calculated as the product of mature males and the proportion of females and their fecundity, summed over all ages, that is

$$E(t) = \sum_a mat_a fec_a fem_a N_a(t),$$

where fec_a was the fecundity of females-at-age, fem_a was the proportion of females-at-age and mat_a was the proportion of mature males-at-age. This indirectly assumes that the number of successfully fertilized eggs produced by a female of age a is proportional to the ratio of males-at-age a, summed over all ages.

The parameters α, β in the reproduction curve were represented by a steepness parameter h (fixed at 0.7, see Tanimoto *et al*. 2012) and an initial recruitment parameter R_0, where

$$\alpha = \frac{\bar{E}}{R_0}\left(\frac{1-h}{4h}\right), \quad \beta = \frac{5h-1}{4hR_0},$$

where $\bar{E}$ is the egg production over the lifespan of R_0 recruits in an unfished environment.

3.4. Model Calibration

In the calibration phase of the model, the virgin-recruitment parameter R_0 (recruitment in virgin year); the von Bertalanffy parameters: L_∞ (average maximum length), k (growth coefficient) and a_0[1] (determining the initial length), as well as the standard deviation in the length-to-age distribution σ; and the recruitment variation parameters $\epsilon(t)$ (recruitment variation) and $\hat{\sigma}$ (standard deviation in recruitment variation) were estimated.

The parameters were estimated following a Bayesian approach, by minimising the negative log likelihood fitted to standardised catch rates and, where available, age-frequency data. The estimation was executed by a Monte Carlo Markov Chain (MCMC) method using the Metropolis-Hastings algorithm for 10^5 MCMC simulations in each parameter set. A burn in of 1000 and a thinning of 23 were applied for the analysis, passing an autocorrelation test. The prior distribution assumed a normal distribution with parameter specific ranges. These parameter ranges were chosen based on knowledge of the life history of barramundi, previous barramundi stock assessments (Campbell *et al.,* 2008; Campbell *et al.,* 2017), and realistic model results regarding the stock abundance.

Visual examination of the MCMC parameter traces and inbuilt functions of the R package ‘coda’ based on MCMC convergence tests by Geweke, Heidelberger and Welch and Gelman, were used to investigate the convergence of the MCMC and identify a model that was in concordance with input data. The parameter estimates obtained from the MCMC analysis (excluding the burn in phase) were used to calculate stock status indicators and their standard deviations. For the calculation of MSY values, no recruitment variation was considered.

For the projection phase, the mean of the recruitment variation of the last five years (2013 to 2017) was applied. For each stock, the final model selected (referred to here-after as the base case) satisfied both internal and external consistency criteria and led to reasonable values of the stock

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[1] To reduce the autocorrelation in the calibration phase between k and a_0, a new parameter $t_0 = -ka_0$ was introduced to estimate t_0 and k instead of k and a_0. The reported a_0 is hence $-t_0/k$.

status indicators. Here, internal consistency refers to generated outputs for stock status indicators exhibiting complementary trends (i.e., across all indicators within a stock) over time and external consistency refers to sufficient degree of agreement with previous studies (e.g., Gribble 2004; Campbell *et al.,* 2008; Tanimoto *et al*., 2012; Campbell *et al.,* 2017).

The model was fitted to standardised annual catch rates for the years 1988 to 2017 for East Coast stocks and from 1989 to 2017 for Gulf stocks[2]. The population models for the East Coast stocks (NEC, Mackay, CEC) and the Southern Gulf were also fitted to annual age-frequency data. The age-at-length relationship was fitted inside the model due to the selectivity bias that results from fishery-dependent sampling of age-length data by Fishery Monitoring.

For the Mackay stock, we assumed that barramundi grow at a similar rate to that of the adjacent North East Coast. This resulted in the model for the Mackay stock being fitted to the age-length data sampled from the adjacent NEC.

Age-frequency data collected in the Central East Coast stock past 2010 were not used during model fitting to avoid a distortion of age-frequency data of wild barramundi mixed with the age-frequency data of barramundi that had escaped from Awoonga Dam in 2010/11.

Due to a lack of available age-length data for the Northern Gulf stock, no recruitment variation was considered ($\epsilon = \hat{\sigma} = 0$) and the model was fitted solely to standardised catch rates.

The model's annual catch rate was obtained by multiplying a catchability factor (q) to the modelled exploitable biomass. This factor was calculated as the geometric mean of standardised catch rate divided by modelled exploitable biomass. Thus,

$$catch\ rate_{Model}(t) = qB_t,$$

where q was calculated as

$$q = \prod_t \frac{catch\ rate_{Observed}(t)}{B_t}.$$

The model predicted the annual age-frequency that was commercially caught and therefore subject to selectivity constraints, as

$$A_a(t) = \frac{C_a(t)}{\sum_a C_a(t)} = \frac{S_a N_a(t) U(t)}{\sum_a S_a N_a(t) U(t)}$$

The model was fitted in a standard statistical fashion by minimizing negative log-likelihood components (indicated by L) that were combined additively including penalties (denoted by Pen).

The total objective function (TOF) consisting of the negative log-likelihoods was

$$TOF = -\log(L_{\text{catch rate}}) - \log(L_{\text{age}}) + \mathrm{Pen_B} + \ \mathrm{Pen_R} + Pen_V,$$

with

$$-\log(L_{\text{catch rate}}) = \frac{n}{2}\left(\log(2\pi) + 2\log\left(\frac{1}{n}\sqrt{\sum\nolimits_t \left(\log(\text{catch rate}) - \log(\widehat{\text{catch rate}})\right)^2}\ \right) + 1\right).$$

This assumed that the difference between the modelled catch rate and observed $\widehat{\text{catch rate}}$ was normal distributed, i.e., $\text{catch rate} - \widehat{\text{catch rate}} \sim N(0, \sigma^2_{catch\ rate})$. Here, $n = 30$ as it spans the years 1988 to 2017 for east coast stocks and $n = 29$ for Gulf stocks.

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[2] The model was fitted to annual standardised catch calculated as the average over the monthly standardised catch rates, as described in detail in Appendix C.

The term

$$-\log(L_{\text{age}}) = -\frac{m_a - 1}{2}\log\left(\frac{m_a - 1}{2\sum_a \widehat{A_a}(\log \widehat{A_a} - \log A_a)}\right)$$

where A_a was the modelled frequency-at-age and $\widehat{A_a}$ was the observed frequency-at-age given by the Fishery Monitoring data, here $m_a = 25$ (i.e., maximum age). The derivation was based on the assumption that frequency-at-age at time t follows a multinomial distribution, which was then modified by an effective sample size (Leigh *et al*., 2017).

To avoid unrealistic model fits, penalty functions were used. The first penalty acted on parameter fits that resulted in modelled biomass that was smaller than the observed catch. The corresponding penalty function was

$$\text{Pen}_\text{B} = \sum_{\tau:\hat{C}_\tau > B_\tau} 0.1\log^2\left(\frac{0.05B_\tau}{\hat{C}_\tau}\right)$$

The parameters 0.05 and 0.1 were chosen to balance the penalty with the other likelihood functions. A second penalty function prevented unrealistically large values of recruitment R_t. The corresponding penalty function only contributed to the fitting process if the observed catch was smaller than five per cent of the recruitment biomass, that is

$$\text{Pen}_\text{R} = \sum_{\tau:\ \theta w R_\tau > \hat{C}_\tau} \log^2\left(\frac{\theta R_\tau w}{\hat{C}_\tau}\right)$$

where $\theta = 0.05$ can be interpreted as the minimum harvest rate, see Tanimoto *et al*. (2012).

The last penalty function was implemented to avoid unrealistically large variation in recruitment. The penalty function was

$$Pen_V = \sum_\tau \log(\hat{\sigma}) + 0.5\frac{\epsilon(t)}{\hat{\sigma}},$$

in concordance with Shirripa *et al*., (2009) and Campbell *et al.,* (2017).

3.5. Assumptions and Limitations

Outputs from the model are underpinned by the following assumptions and limitations and should be considered when interpreting the results.

a) Virgin ratio and historical data

Only limited data and anecdotal reports are available upon which to base estimates of catch and/or effort in/from Queensland barramundi stocks prior to 1980. This poses a dilemma for any stock assessment of barramundi stocks in Queensland and forces the need for an assumption of either: (i) using reconstructed historic catch and/or effort to model population dynamics of the stock from the start of fishing (as per Campbell *et al*., 2017); or (ii) assuming a certain level of biomass at some point in time after fishing started (as per Gribble 2004; Campbell *et al*., 2008).

Historical catch (i.e., pre 1988) was collated/estimated for each stock based on available information and data (see Appendix D). Attempts to optimise the model to the reconstructed historical catch data (see Appendix D) produced unreasonable model fits. There are several possible reasons (e.g., inaccurate catch/effort estimates based on the limited available data or temporal changes in the relationship between catch and effort from the start of the fishery to present). The historic catch estimates were considered to have insufficient reliability to be used in the assessment for any of the Queensland barramundi stocks under current model configuration (which differs slightly to that of Campbell *et al*., 2017).

Instead, we assumed a starting exploitable biomass to virgin biomass ratio (i.e., the initial depletion rate denoted by ψ). For the Queensland east coast stocks, we assumed a depletion rate of $\psi = 0.25$ in 1988. For Gulf stocks, we assumed a depletion rate of $\psi = 0.2$ in 1989; similar to that assumed by Gribble (2004) and Campbell *et al.* (2008). We assumed an equivalent rate of depletion in the starting egg production to virgin egg production ratio. These are significant assumptions of the model, and results could be different if the assumed depletion rates are incorrect. As such, alternate starting depletion rates were considered during sensitivity testing of the model, see Section 3.6.

In general, if the initial biomass was more depleted, then the model estimated B/B_0 would be lower. If the biomass in 1988 (or 1989 in the Gulf) were less depleted, then estimated B/B_0 would be higher.

b) Constant relationship between catch and effort i.e., 'catchability'

A widely used relationship in stock assessment modelling is the Schaefer equation, which postulates that catch is proportional to abundance and effort (Schaefer 1954). This relationship was indirectly incorporated in our model, by assuming a constant catchability (q) which implies that an increase in catch rate reflects an increase in biomass. Often, this is a valid assumption.

However, not all factors that affect catchability may be captured in the standardised catch rate and thus this could lead to an over or under estimation of biomass. For instance, technological advances that assist in finding a productive fishing location could have such an effect. Other aspects that could increase the catchability in a net fishery are the degree to which nets are 'actively worked', decreases in competition due to changing fisher participation, and environmental factors such as river discharge. In order to address changes in catchability that are currently unknown, a scenario testing model sensitivity to increasing catchability (q_{inc}) was considered, see Section 3.6.

c) Recreational harvest

Recreational fishing harvest was not incorporated in the base case model of the current stock assessment because of insufficient and uncertain time series of retained catch (and effort). In the most recent State Wide Recreational Fishing Survey (SWRFS), the barramundi harvest for Queensland-based recreational fishers was estimated as 131 tonnes compared to a total commercial harvest across all stocks of 762 tonnes (Webley *et al.,* 2015). Although the comparably low state wide recreational harvest (compared to commercial harvest) supports a model based on commercial catch, especially given the uncertainty in recreational harvest data, two scenarios incorporating recreational harvest were considered, see Section 3.6.

d) Stocked fish

The impacts of barramundi stocked as fingerlings into upstream impoundments and waterway was not considered in the current population model for any stock except the Central East Coast. The escape of barramundi from Awoonga Dam in 2010/11 (and 2012) significantly changed the catch and standardised catch rate in this stock and would cause spurious biomass estimates if not accounted for. The survival of stocked barramundi is uncertain. Therefore, the annual catch time series for 2011 to 2015 were smoothed to account for the distorted time series of catch caused by the contribution of stocked fish in the CFISH logbook database for the years following the flooding.

If the annual catch of the non-stocked barramundi was higher than the assumed smoothed catch in any of the years 2011 to 2015, then the fishing pressure would also have been higher than that currently considered. This in turn would have resulted most likely in a reduction of the exploitable biomass, which reduces the overall abundance. Further information, such as the contribution of stocked fish to the catch between 2011 and 2015 would be needed to identify any significant deviations from the model's projections. In addition, the Capricorn Coast net-free zone was introduced in November 2015 and changed the scale and distribution of fishing effort in the Central East Coast stock (and other stocks). The current assessment considers two years of catch data post the introduction of the Capricorn Coast net-free zone and length and age data are no longer collected from the commercial barramundi fishery for this stock by Fishery Monitoring. Therefore, the current assessment cannot model the effects of the net-free zone.

e) Influences of rainfall/river flow

Rainfall or river flow was not incorporated into the current population model. However, annual variations in the survival of recruits has been implemented by a time-dependent model estimated recruitment variation parameter. Therefore, estimated model outputs are insensitive to the explicit influences of rainfall and river. However, results do implicitly reflect the long-term dynamics and productivity of the Queensland barramundi stocks modelled in the current assessment.

3.6. Model Scenario Analysis

To address the assumptions and limitations mentioned in Section 3.5 and their effects on model results, the model was fitted to different scenarios. For each scenario, the model was refitted with the same total objective function as in the base case, using the same prior distributions for the model-estimated parameters.

a) Depletion rate

In order to analyse the impact of the assumed starting depletion rate (ψ), rates that implied both greater and lesser depletion in 1988/1989 were also trialled. For the Gulf stocks, the scenario of a greater depletion rate was implemented by assuming an exploitable biomass level in 1989 of 0.1 of the virgin biomass, while for the East Coast stocks, the assumption for this scenario was an exploitable biomass level in 1988 of 0.15. In all stocks, these greater depletion rates led to reduced biomass ratios and lower egg production ratios.

The case of a lesser depletion rate in 1988/1989 was also investigated. In that scenario, the assumption was that the biomass level was at 0.30 of virgin biomass for the Gulf stocks and 0.35 of virgin biomass for the East Coast stocks. This scenario, corresponding to an increase in the starting biomass level in 1988/1989, led to higher biomass ratios and egg production ratios across all years and all stocks.

b) Increasing catchability

Schaefer's assumption that catch is proportional to abundance multiplied by effort implies that abundance is proportional to catch divided by effort. The proportionality constant is often referred to as “catchability parameter”. Catchability is rarely constant for different fishers and different conditions, which is why a standardisation of the catch rate is performed. Even though variations among fishers, location, time and net-length are accounted for in the standardisation of the catch rate, the remaining assumption is that the catchability is constant over time.

The assumption of a constant catchability is crucial, as it implies that changes in the standardised catch rate are due to changes in the abundance. Given the increase in the standardised catch rate for all stocks, this assumption implies a recovery trend in biomass. As mentioned in the model assumptions, if in fact a steady improvement of the catchability due to, for example, technical advances or a long-term environmental trend, is responsible for the increasing trend in the standardised catch rate, the model could overestimate the biomass levels.

We therefore considered a scenario of an increase in catchability over time. The following multiplicative relationship for the “catchability parameter” q was considered:

$$q_t = q_0 \cdot \exp(\hat{t} \cdot q_{inc})$$

where $q_0 = \prod_{\tau=t_0}^{t_0+5} \left(\frac{\widehat{cpue}_\tau}{B_\tau}\right)^{1/6}$ is the geometric mean of the ratio of standardised catch rate and modelled biomass in the first six years and $\hat{t} = \frac{t-t_0}{2018-t_0}$ is the normalized change in time. The initial index t_0 is 1988 for the East Coast stocks and 1989 for the Gulf stocks. The parameter q_{inc} has been estimated as part of the MCMC analysis. Note that if $q_{inc} = 0$, the scenario is equivalent to the base case.

c) Recreational harvest

Two scenarios were analysed to test the sensitivity of the model results to the possible effects of incorporating recreational harvest. Using recreational survey data (NRIFS and SWRFS) of Queensland residents from 2000, 2011 and 2014[3] and transforming the estimated number of recreationally harvested barramundi into harvest weight using an average fish weight of 3.74 kg on the Queensland east coast, 4.13 kg in the Northern Gulf, and 4.47 kg in the Southern Gulf, mean recreational harvest estimates in tonnes and as percentages of corresponding commercial harvests were derived in Table 1.

Table 1: Recreational harvest estimates per barramundi stock (for each sample year and mean across years) based on National Recreational and Indigenous Fishing Survey (2000) and Statewide Recreational Fishing Survey (2011, 2014) data.*

Harvest (tonnes)*	SGulf	NGulf	NEC	Mack	CEC
2000	143	22	97	29	13
2011	79	17	78	23	10
2014	79	11	46	10	13
Mean harvest (tonnes)	100	17	74	21	12
Mean harvest (% of commercial catch)	17	237	67	37	24

* The harvest tonnages are rounded to integers for presentation, but the model uses data to two decimal places.

The first recreational harvest scenario assumed a constant recreational harvest over time for each stock. For that, the mean across years of the estimated recreational harvests was calculated (Table 1) and was then was then added to the commercial catch in each year to provide a total harvest i.e., recreational and commercial combined. The second scenario assumed that recreational harvest over time follows the same patterns as the commercial catch. For each of the three sample years, the per cent of recreational harvest to commercial catch was calculated and the mean per cent recreational harvest added to the commercial catch in each year for each stock, see Table 1.

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[3] The survey was conducted for the financial years: 1999-2000, 2010-2011, and 2013-2014.

4. Model results

This section summarises modelled trends of key stock status indicators over the 29 years 1989-2017 for the Southern and Northern Gulf stocks and over the 30 years 1988-2017 for the Queensland east coast stocks. The age-structured model results have been cross-validated with simple surplus models for a likely range of initial condition and previous stock assessments (Campbell *et al*., 2017).

We calculate trends over time of the following stock status indicators:

- B/B_0: exploitable biomass to the exploitable biomass before fishing commenced
- E/E_0: egg production to egg production before fishing commenced
- B/B_{msy}: exploitable biomass to the exploitable biomass at maximum sustainable yield
- F/F_{msy}: harvest rate to harvest rate that yields maximum sustainable yield

The biomass $(B_{msy})$and fishing mortality (F_{msy}) at maximum sustainable yield are common reference points calculated in fisheries stock assessments. However, these values are derived under the assumption of long-term equilibrium conditions and may not be appropriate for all species. This is especially so for species that are influenced by environmental changes, which should be modelled with time-dependent parameters in the population model to account for annual changes in the growth and survival. Consequently, biomass interpretation related to equilibrium conditions is not recommended for barramundi (see also Campbell *et al*. 2017). In the current assessment, environmental effects on the survival of young-of-the-year are only partially accounted for by the implementation of a time-dependent recruitment variation parameter. Thus, we caution against reliance on maximum sustainable yield values B_{msy} and F_{msy}.

In the Southern Gulf stock, the estimates of recruitment variation differed between years, ranging in value from 60% of the average recruitment (i.e., reduced initial survival) to 130% of the average recruitment (i.e., increased initial survival). For stock status indicators, we focus primarily on the ratios comparing the exploitable biomass and egg production to their respective values at virgin (i.e., prior to fishing). We also have analysed the age-frequency data, wherever available, see also Section 2.3. It is generally assumed that high values of E/E_0 imply presence of ‘healthy’ numbers of females (and eggs production), and thus give the stock the capacity for strong recruitment (i.e., year-classes).

The main results from the current stock assessment indicate:

1. Queensland’s barramundi stocks generally exhibited a consistent, albeit slowing, pattern of recovery from the assumed starting exploitable biomass rate of 0.25 in 1988 for Queensland east coast stocks and 0.2 in 1989 for Gulf stocks.
2. All stocks were estimated to be very close to or above 0.40 exploitable biomass (relative to virgin) in 2017.
3. Estimates of barramundi egg production ratio, relative to assumed levels in 1988/1989, had increased for most stocks but, typically, only moderately. The egg production ratio had not markedly increased for the North East Coast and the Southern Gulf stocks. However, it is uncertain what is an appropriate E/E_0 for a long-lived protandrous hermaphrodite species like barramundi that also has very high fecundity.
4. Climatic events such as flooding and droughts may have caused significant fluctuations in exploitable biomass and recruitment especially in the Southern Gulf barramundi stock. Such fluctuations were implicitly considered in the form of model estimated recruitment variations.

5. While the current age-structured model identified the main trends in Queensland barramundi stocks, further analyses of the effects of river flows are likely to improve the accuracy of current exploitable biomass and egg production estimates.

Table 2: Median values of exploitable biomass and egg production ratios estimated for the years 2017 and 2027 under the base case model for each Queensland barramundi stock assessed.

Genetic Stock	B/B_0 in 2017	E/E_0 in 2017	Average harvest (2013-2017)	B/B_0 in 2027 for TACC^{*5}	E/E_0 in 2027 for TACC^{*5}	TACC for $B/B_0 = 0.60$ in 2027
SGulf	0.39	0.29	468 t	0.50	0.40	$\leq 468^{***}$ t
NGulf	0.73	0.61	19 t	0.81	0.68	≤ 40 t
NEC	0.53	0.25	81 t	0.63	0.38	≤ 88 t
Mack	0.59	0.43	82 t	0.57	0.39	≤ 75 t
CEC	0.71	0.50	58** t	0.73	0.52	≤ 75 t

^{*5} corresponds to the 5-year average (2013-2017); **indicates that this value is obtained from the adjusted mean time series; ***indicates that this attains only the lower biomass target of 0.50.

4.1. Southern Gulf

4.1.1. Stock status indicator results

In the stock status indicator plots (Figure 17), the solid black line displays the median of the model-simulated trends. The grey shaded area illustrates the 10 per cent to 90 per cent percentile rank, that is, the range in which 80 per cent of the simulations were contained.

Figure 17 presents the exploitable biomass B relative to the exploitable biomass in virgin year B_0 and the egg production E relative to the egg production in virgin year E_0. For the Southern Gulf barramundi stock, the biomass ratio follows an increasing trend, while the egg production ratio recovers more slowly. Note that the initial drop in the exploitable biomass and egg production ratios stems from the assumption of a very depleted stock in 1989 (i.e., at 0.2 of virgin biomass) and is caused by the momentum of that depletion. Therefore, the relative harvest rate increases until 1990 (Figure 2). There is about a three-year lag before the recovery due to new recruitment manifests itself in exploitable biomass.

The important features in Figure 17 were:

- Increases in exploitable biomass and egg production ratios since the introduction of management changes in 1992, which included the introduction of a formal maximum legal size. The increase in the egg production ratio being less pronounced than that seen for exploitable biomass.
- The exploitable biomass ratio B/B_0 increased from the assumed 0.2 in 1989 to 0.39 in 2017. This is below the Sustainable Fisheries Strategy target of 0.60 by 2027, but is close to the target of 0.40 by 2020.
- The egg production ratio E/E_0 exhibits an increasing trend after an initial decline due to the significant assumption of an initial depletion rate of 0.2 in 1989. The depleted age-classes of barramundi that contribute to egg-production (i.e., predominantly fish greater than six years old) take time to replenish.
- The egg production ratio E/E_0 was still relatively low at 0.29 in 2017.
- Modelled biomass trends between 1990 and 2008 agrees closely with that reported by in Campbell *et al.* (2008).

We also report B/B_{msy} which is exploitable biomass compared to the exploitable biomass at maximum sustainable yield, noting that B_{MSY}/B_0 = 0.5. In 2017, B/B_{msy} was estimated at 0.68 (Table 3). For the majority of years, F/F_{msy} is below one (Table 3), which allows the biomass to increase.

Table 3: Southern Gulf barramundi stock median values of stock status indicators for selected years.

SGulf	1989	1995	2000	2005	2010	2015	2017
B/B_0	0.20	0.21	0.32	0.30	0.45	0.30	0.39
E/E_0	0.20	0.15	0.19	0.21	0.26	0.29	0.29
B/B_{msy}	0.38	0.37	0.53	0.51	0.77	0.52	0.68
F/F_{msy}	0.80	0.69	0.68	0.54	0.58	0.41	0.54

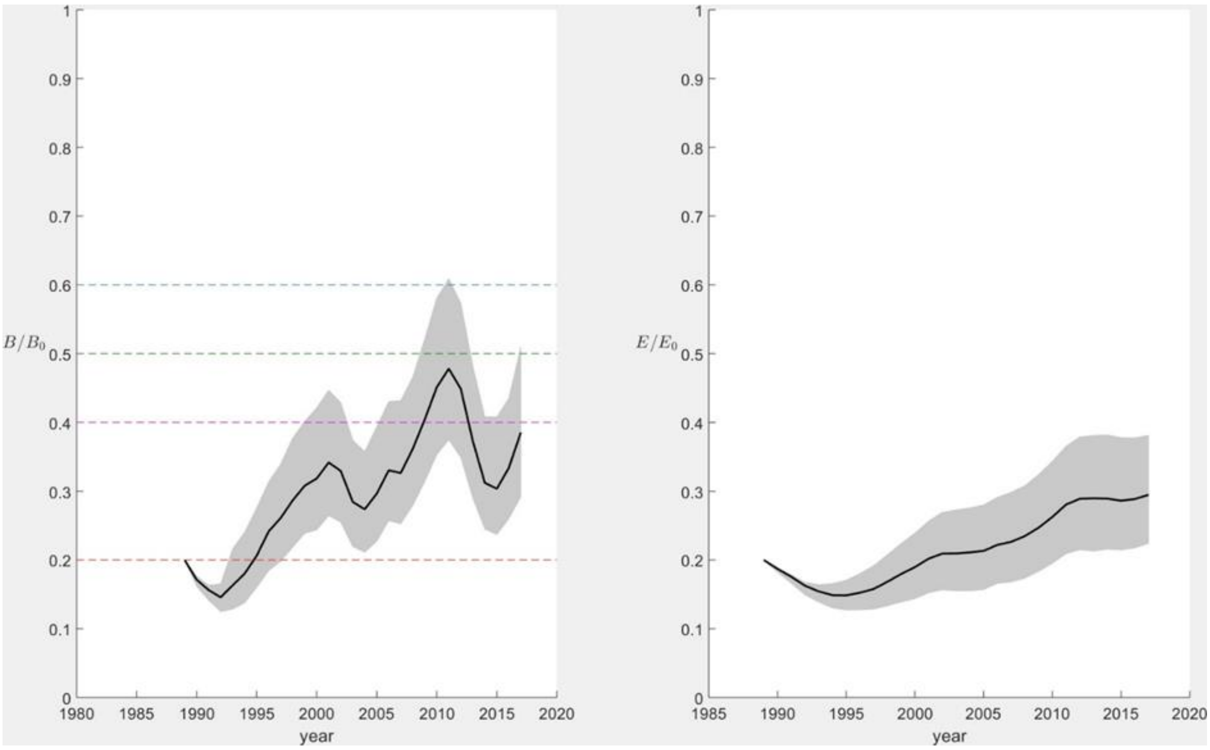

Figure 17: Southern Gulf barramundi stock status indicators. The blue dashed line is the 60 per cent 2027 target of the SFS, the green dashed line is the 50 per cent biomass ratio (MSY), the pink dashed line is the 40 per cent 2020 target of the SFS and the red dashed line is the 20 per cent biomass ratio (Commonwealth limit reference point).

4.1.2. Goodness-of-Fit

Goodness-of-fit to the average annual standardised catch rate data are displayed in Figure 18. For the Southern Gulf stock, the current population model captures the main patterns over time in catch rate, although misses some of the variation associated with the observed peaks and troughs.

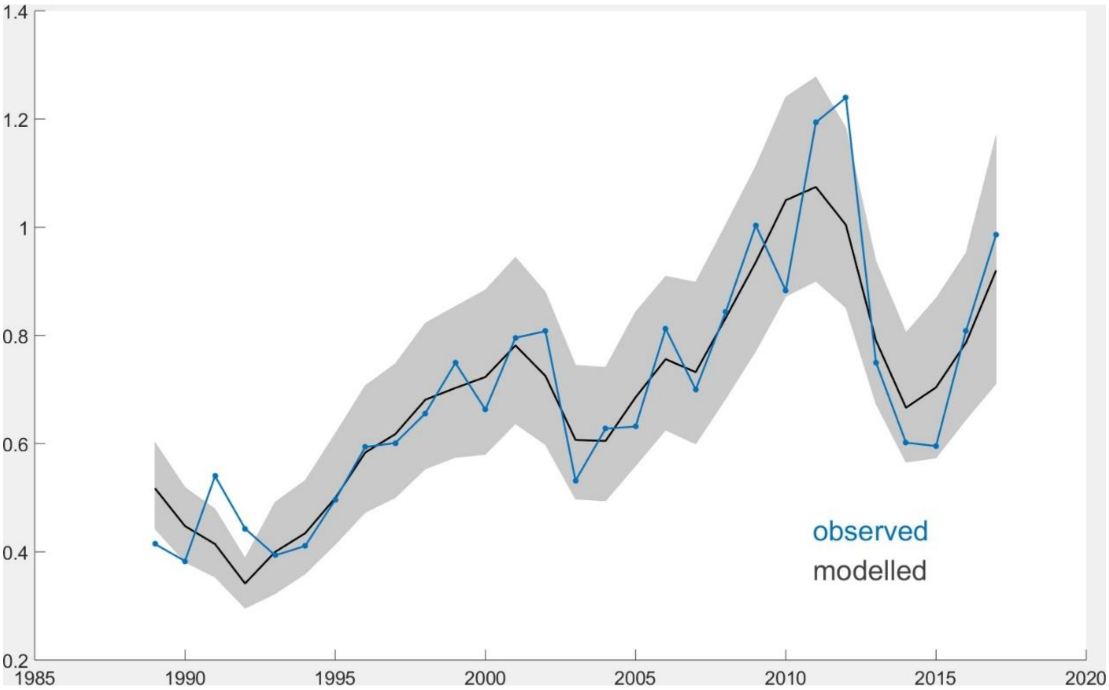

Figure 18: Southern Gulf barramundi stock standardised catch rate goodness-of-fit where the observed annual standardised catch rate is the blue line and modelled estimated is the black line.

Goodness-of-fit to the Fishery Monitoring age-frequency data for 2007 to 2017 are displayed in Figure 19. This figure indicates that the current population model (through its use of model-fitted recruitment variation) captures much, but not all, of the patterns in the age-frequency data.

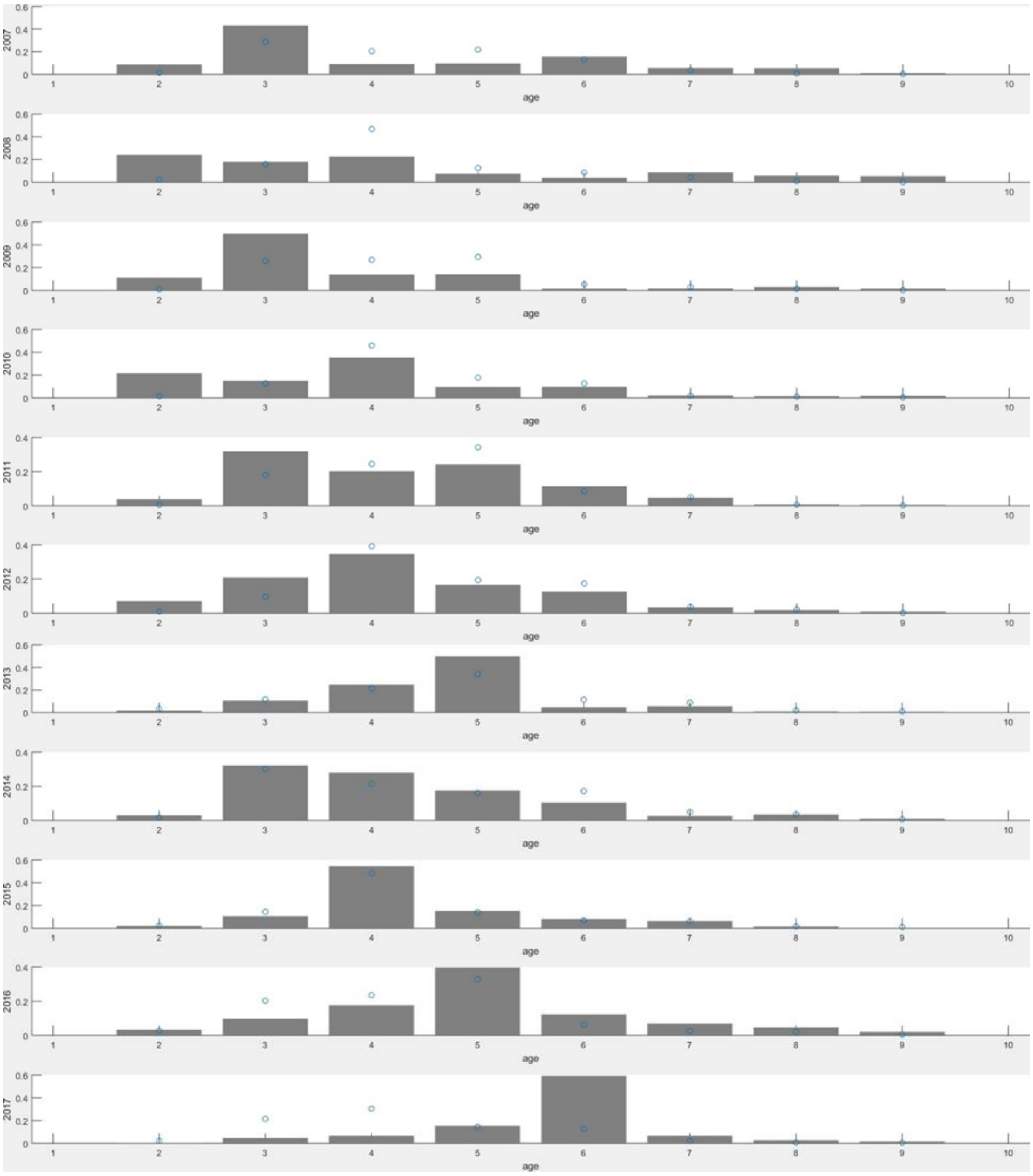

Figure 19: Southern Gulf barramundi stock age-frequency goodness-of-fit where observed data are the bars and modelled estimated data are the circles. Note the change in y-axis scale between years.

4.1.3. Total Allowable Commercial Catch (TACC) Scenarios

Predicted trends in exploitable biomass for the Southern Gulf stock under three alternate scenarios of constant Total Allowable Commercial Catch (TACC) were investigated (Figure 20).

A constant TACC of 300 tonnes yields an exploitable biomass ratio B/B_0 of 0.52 by 2027 with an increasing trend.

A TACC of 468 tonnes (i.e., the average catch of the last five years = 2013 to 2017) yields a B/B_0 of 0.5 in 2023 which stabilises (i.e., will be 0.5 in 2027).

A TACC of 614 tonnes (i.e., the 2017 catch) yields a biomass ratio of 0.4 in 2027. A similar result is predicted if 642 tonnes were annually harvested, the average of the past 10 years.

A specific feature of the Southern Gulf stock for the forward projections under various TACC's is the large variance around the median estimate (i.e., grey area in Figure 20 surrounding the black line) for the years 2019 to 2022. This variance is due to the time dependent recruitment variation parameter $\epsilon(t)$. Specifically, at the end of the time series (2014 to 2017), the recruitment variation parameter $\epsilon(t)$ shows deviations which ultimately lead to large variations in recruitment in the early years of the 2018-2028 projection phase. As the first cohort of the projection phase enters the exploitable biomass at around age three (in 2021), the variance shrinks and stabilizes, because future forecasts assume constant recruitment variation[4]. In future developments, linking recruitment variations to environmental drivers could improve the abundance predictions and reduce the above variance around the median estimate.

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[4] The projection phase assumes constant recruitment variation and is the mean of the model-estimated recruitment variation of the last five years (i.e., 2013 to 2017).

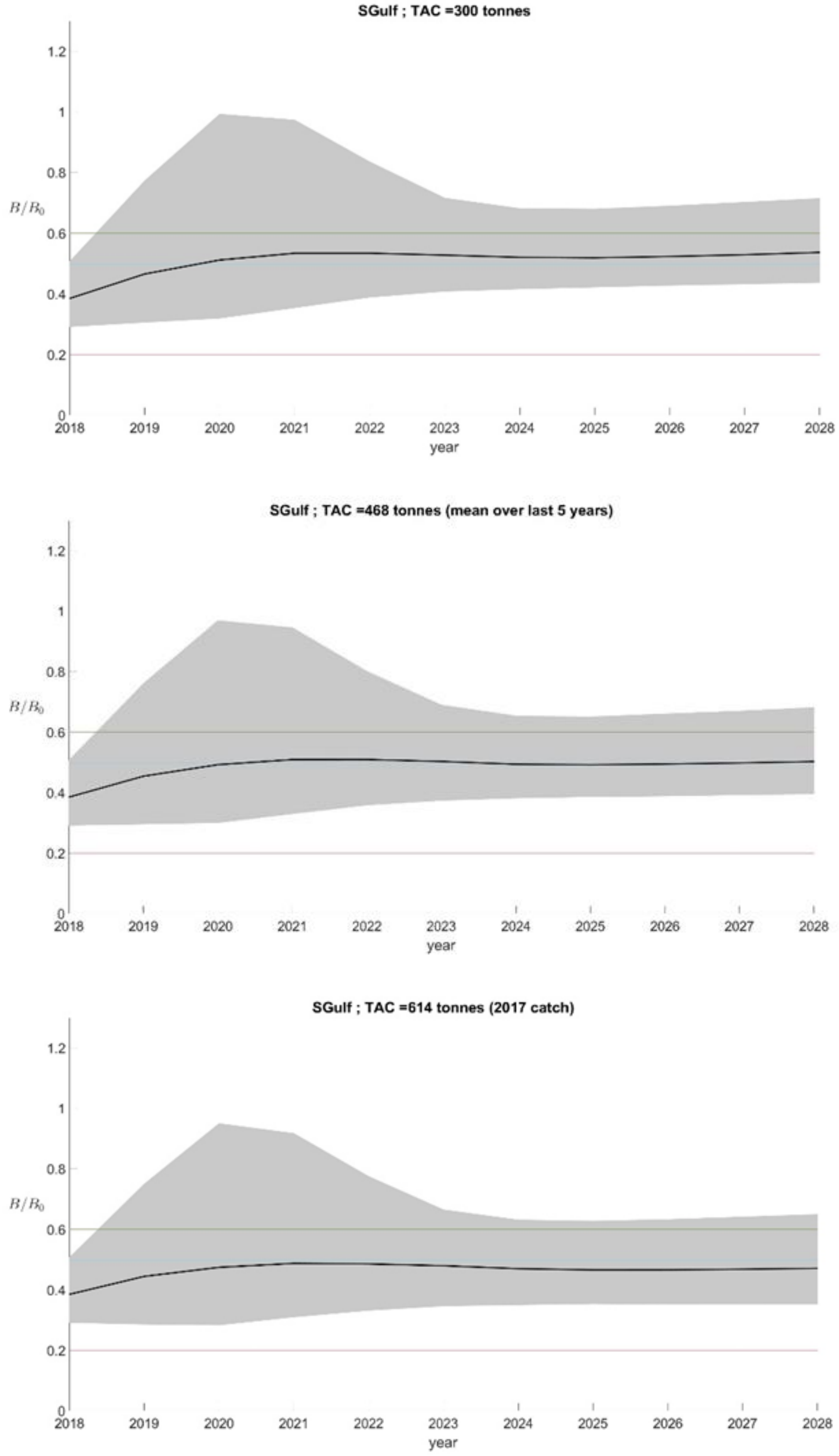


Figure 20: Southern Gulf barramundi stock modelled effects of constant Total Allowable Commercial Catch (TACC) for (a) 300 tonnes, (b) 468 tonnes, and (c) 614 tonnes on the projected exploitable biomass to virgin biomass ratio 2018 to 2028.

4.1.4. Sensitivity Analysis

Three different types of scenarios were investigated for sensitivity to the model assumptions. The refitted model parameter estimates, for all scenarios, are presented in Appendix F, Table 16. Stock status indicators are presented in Table 4 and Figure 21.

Sensitivity testing indicates that for the Southern Gulf barramundi stock, estimated results were most sensitive to the assumed initial depletion rate (ψ), somewhat sensitive to a changing catchability q_{inc} , but relatively insensitive to the incorporation of recreational harvest. Consistent across all scenarios and the base case was the recovery pattern in B/B_0 and a slower recovery pattern in E/E_0.

a) Initial depletion rate ($\psi_{low} = 0.1$, $\psi_{high} = 0.3$)

The sensitivity testing indicated that model results for the Southern Gulf stock are highly sensitive to the assumed initial depletion rate (ψ). Recall, from Section 3.5, that ψ represents B_{1989}/B_0 . Under the base case scenario of ($\psi = 0.2$), the biomass ratio B/B_0 of the Southern Gulf barramundi stock was estimated in 2017 to be 0.39.

When the stock was assumed to be more depleted ($\psi_{low} = 0.1$ in 1989) the biomass ratio was estimated in 2017 to be 0.17; while if the stock was assumed to be less depleted ($\psi_{high} = 0.3$ in 1989) the biomass ratio was estimated in 2017 to be 0.61 (Table 4).

Similar results were observed for the egg production ratio E/E_0. If the stock was more depleted, E/E_0 was estimated in 2017 to be 0.10 compared to 0.29 for the base case. If the stock was less depleted, E/E_0 was estimated in 2017to be 0.50.

b) Increase in catchability (q_{inc})

The catchability parameter was estimated at 0.324, corresponding to a catchability in 2017 of 1.38 times the mean catchability of the first five years of CFISH data, see Section 3.6.

For an increasing catchability, the exploitable biomass ratio B/B_0 was estimated in 2017 to be 0.26, compared to 0.39 for the base case. This is only 66 per cent of the estimated ratio for the base case.

Similarly, the egg production ratio E/E_0 was estimated in 2017 to be 0.19, which is a reduction compared to the estimated E/E_0 of 0.29 for the base case (Table 4).

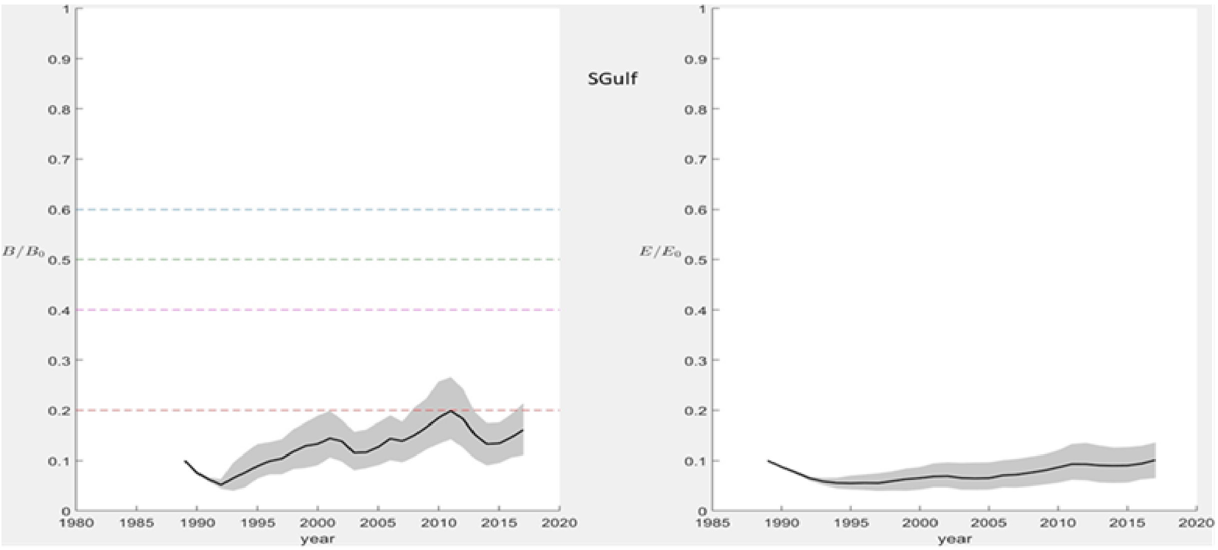
c) Recreational harvest

For the Southern Gulf barramundi stock, recreational harvest was estimated to be relatively low compared to the commercial harvest (by either tonnage or proportion, see Table 1 and Section 3.6). Neither of the two recreational harvest sensitivity scenarios resulted in estimated values of exploitable biomass to virgin biomass ratio B/B_0 or egg production ratio E/E_0 in 2017 that were markedly different from base case estimates (Table 4). As such, the model results for the Southern Gulf stock are relatively insensitive to the inclusion of the recreational harvest scenarios considered. This is not to say that recreational harvest has no effect.

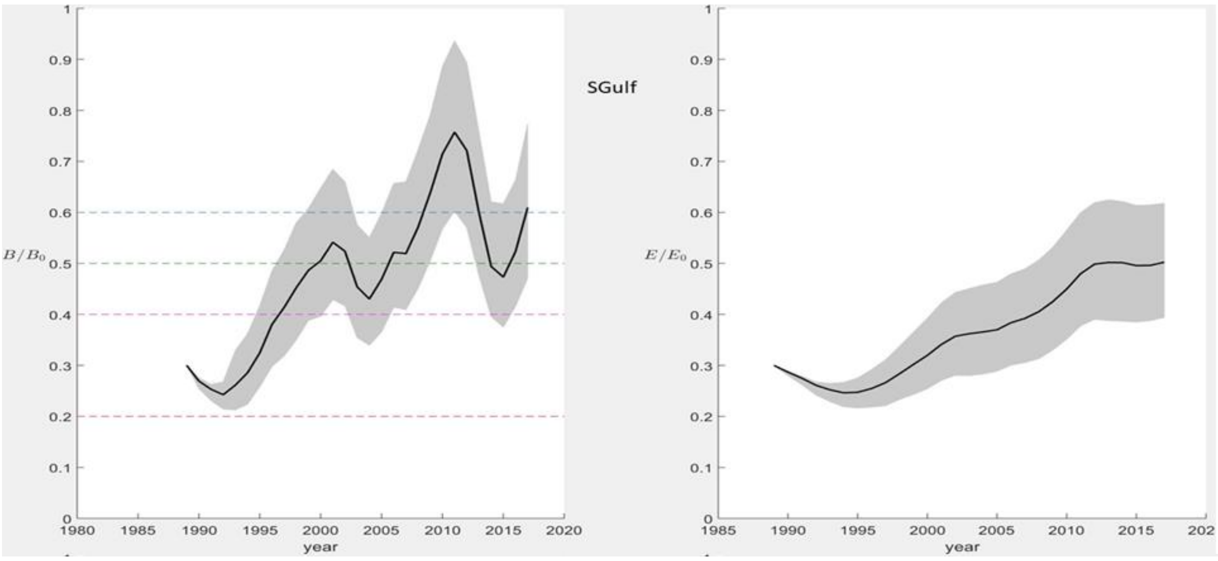
Table 4: Southern Gulf barramundi stock median values of stock status indicators (exploitable biomass to virgin biomass and egg production ratio) estimated under alternate model scenarios for selected years.

SGulf	1989	2005	2008	2012	2015	2017
			Base case			
B/B_0	0.20	0.30	0.36	0.45	0.30	0.39
E/E_0	0.20	0.21	0.23	0.29	0.29	0.29
			Sensitivity results			
$B/B_0\ \psi_{\text{low}}$	0.10	0.13	0.16	0.19	0.14	0.17
$E/E_0\ \psi_{\text{low}}$	0.10	0.07	0.08	0.10	0.09	0.10
$B/B_0\ \psi_{\text{high}}$	0.30	0.47	0.57	0.72	0.47	0.61
$E/E_0\ \psi_{\text{high}}$	0.30	0.37	0.41	0.50	0.50	0.50
$B/B_0\ q_{inc}$	0.20	0.23	0.27	0.32	0.21	0.26
$E/E_0\ q_{inc}$	0.20	0.16	0.17	0.20	0.19	0.19
B/B_0+ Rec con	0.20	0.29	0.35	0.44	0.30	0.37
E/E_0+ Rec con	0.20	0.20	0.22	0.27	0.27	0.28
B/B_0+ Rec prop	0.20	0.29	0.35	0.43	0.30	0.37
E/E_0+ Rec prop	0.20	0.20	0.22	0.27	0.27	0.28

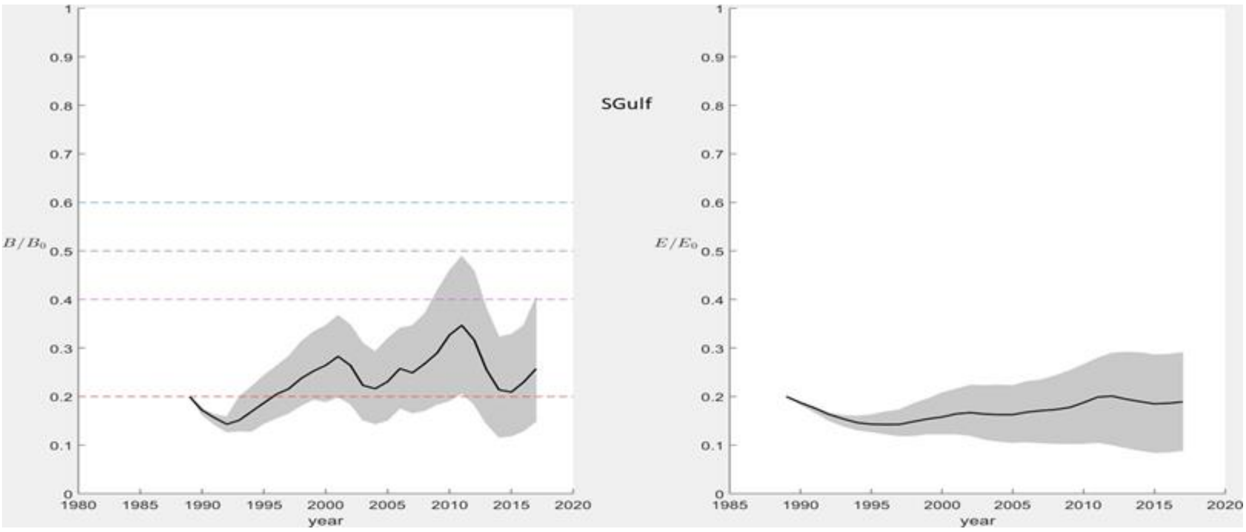
a) Greater depletion rate ($\psi_{\text{low}} = 0.1$)



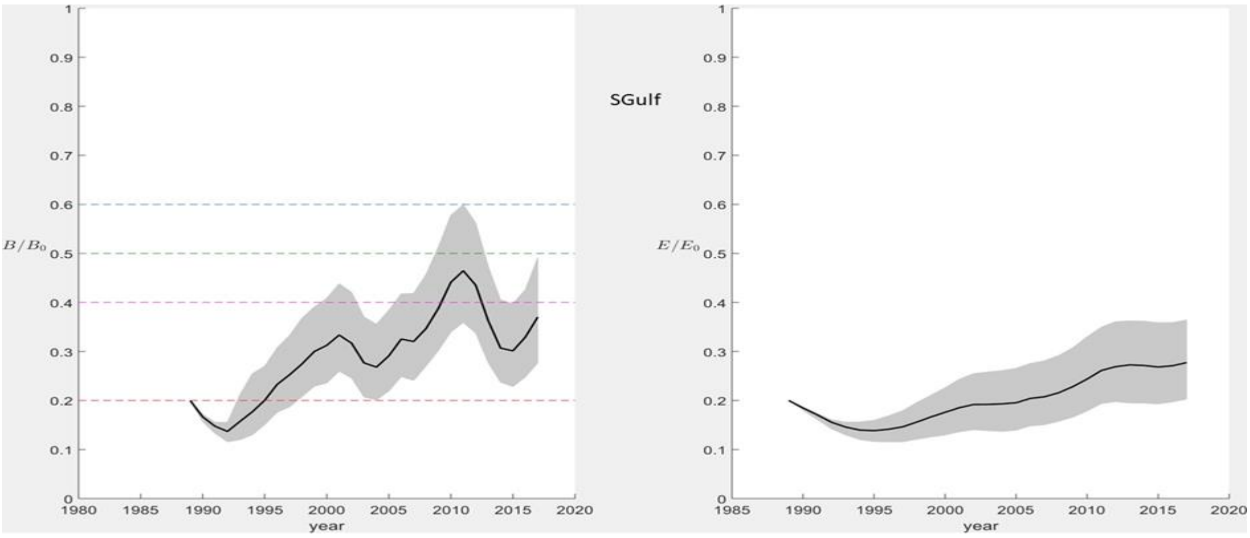
b) Lesser depletion rate ($\psi_{high} = 0.3$)



c) Increasing catchability (q_{inc})



d) Recreational harvest – addition of constant harvest = 100 tonnes



e) Recreational harvest – addition of constant proportion = 17 per cent

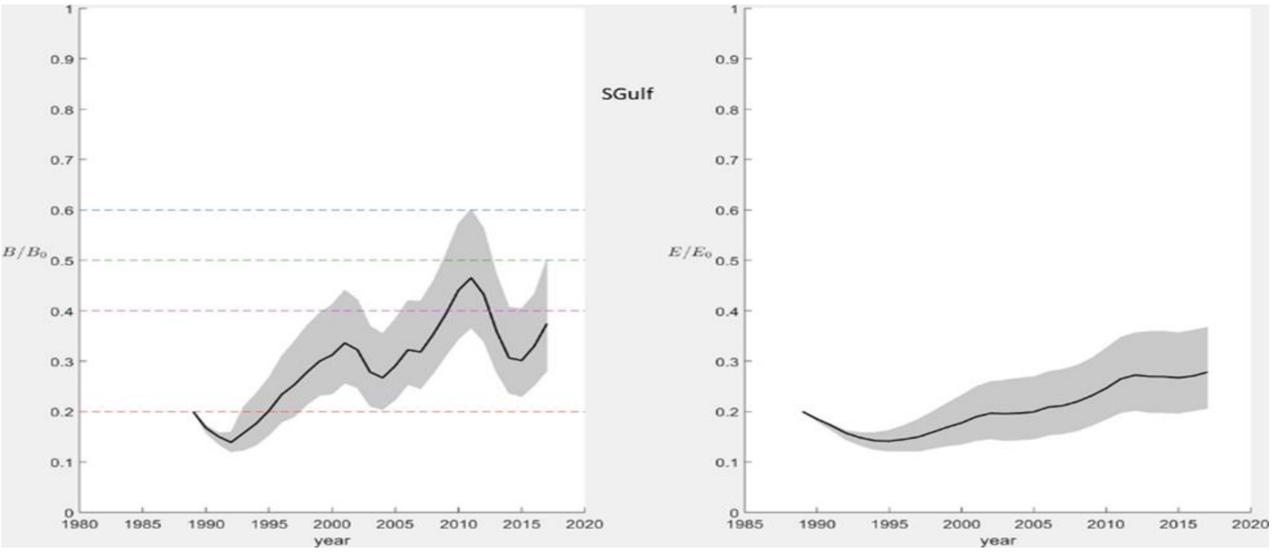


Figure 21: Sensitivity analysis of Southern Gulf barramundi stock status indicators B/B_0 and E/E_0 for (a) greater depletion, (b) lesser depletion, (c) increased catchability, (d) recreational harvest constant tonnage, and (e) recreational harvest constant proportion. The blue dashed line is the 60 per cent 2027 target of the SFS, the green dashed line is the 50 per cent biomass ratio (MSY), the pink dashed line is 40 per cent 2020 target of the SFS and red dashed line is the 20 per cent biomass ratio (Commonwealth limit reference point).

4.2. Northern Gulf

The results for the Northern Gulf stock should be interpreted with caution due to the limited fishing effort and therefore the small number of entries in the CFISH logbook database for this stock. In some years as few as one active authority chain number reported catch and effort (compared to 14 authority chain numbers in other years). This increases the uncertainty in the data in terms of catch rate being representative of fish abundance. Since the model fit is equally weighted to the catch rates for each year, years with few records of catch and effort data can distort the parameter and biomass estimates.

4.2.1. Stock status indicator results

Under the usual model assumptions and the assumption that the available data – even though sparse in parts – are accurately reflecting this stock, the trends in stock status indicators for the Northern Gulf stock are overall higher than in the Southern Gulf (Table 5, Figure 22). The exploitable biomass was at maximum sustainable yield (MSY) in 2012 and has remained above MSY since, as indicated by ratios of $B/B_{msy} \geq 1$ (Table 5).

Table 5: Northern Gulf barramundi stock median values of stock status indicators for selected years.

NGulf	1989	1995	2000	2005	2010	2015	2017
B/B_0	0.20	0.27	0.27	0.51	0.63	0.73	0.73
E/E_0	0.20	0.17	0.17	0.31	0.43	0.58	0.61
B/B_{msy}	0.32	0.48	0.44	0.77	0.95	1.08	1.08
F/F_{msy}	0.50	1.26	0.71	1.24	0.68	0.33	0.77

The egg production ratio E/E_0 in Figure 22 shows a steeply increasing trend from 2000. This trend is directly related to the increase in the exploitable biomass ratio B/B_0 that yields a larger abundance and hence stronger recruitment. We note that the years in which the egg production ratio increases most, are the years following 2000. This behaviour relates to the generally low fishing pressure as apparent in the annual reported catch (Figure 2).

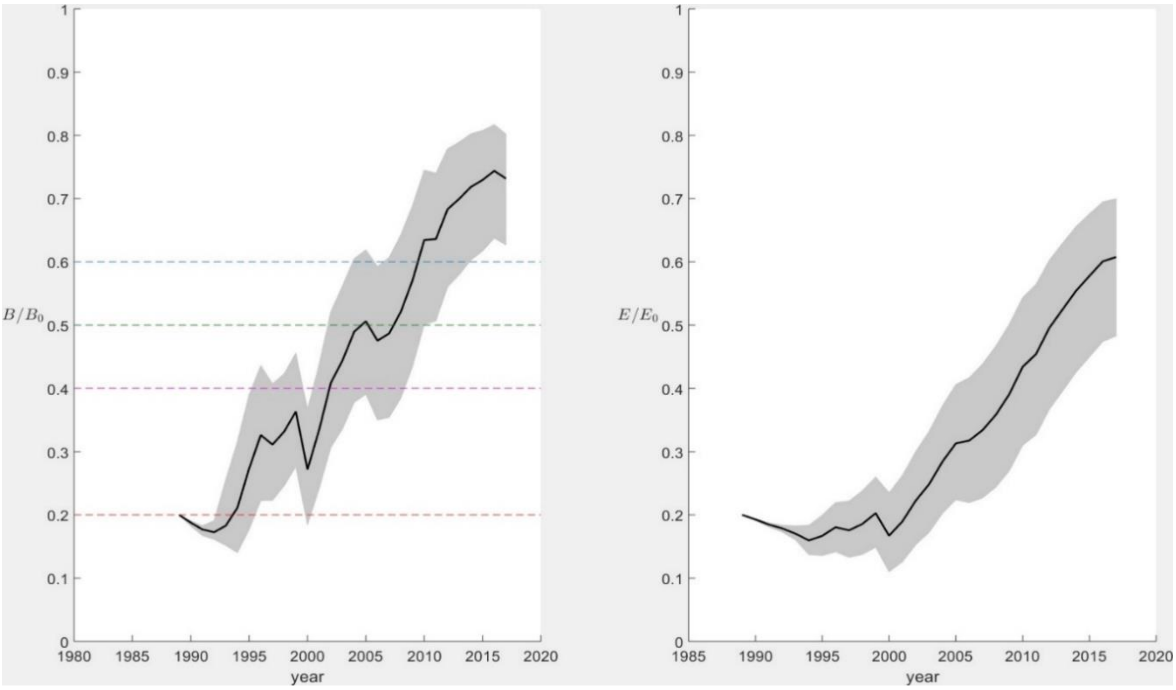


Figure 22: Northern Gulf barramundi stock status indicators. The blue dashed line is the 60 per cent 2027 target of the SFS, the green dashed line is the 50 per cent biomass ratio (MSY), the pink dashed line is the 40 per cent 2020 target of the SFS and the red dashed line is the 20 per cent biomass ratio (Commonwealth limit reference point).

4.2.2. Goodness-of-Fit

There is no age-frequency data for the Northern Gulf stock and the age-length relationship is different to that of the Southern Gulf stock (Davis 1984a). Therefore, for the Northern Gulf stock, the model is solely fitted to the annual standardised catch rates (see Section 2.2). While the model tracks the overall recovery trend, it misses some of the spikes in the observed annual standardised catch rates Figure 23.

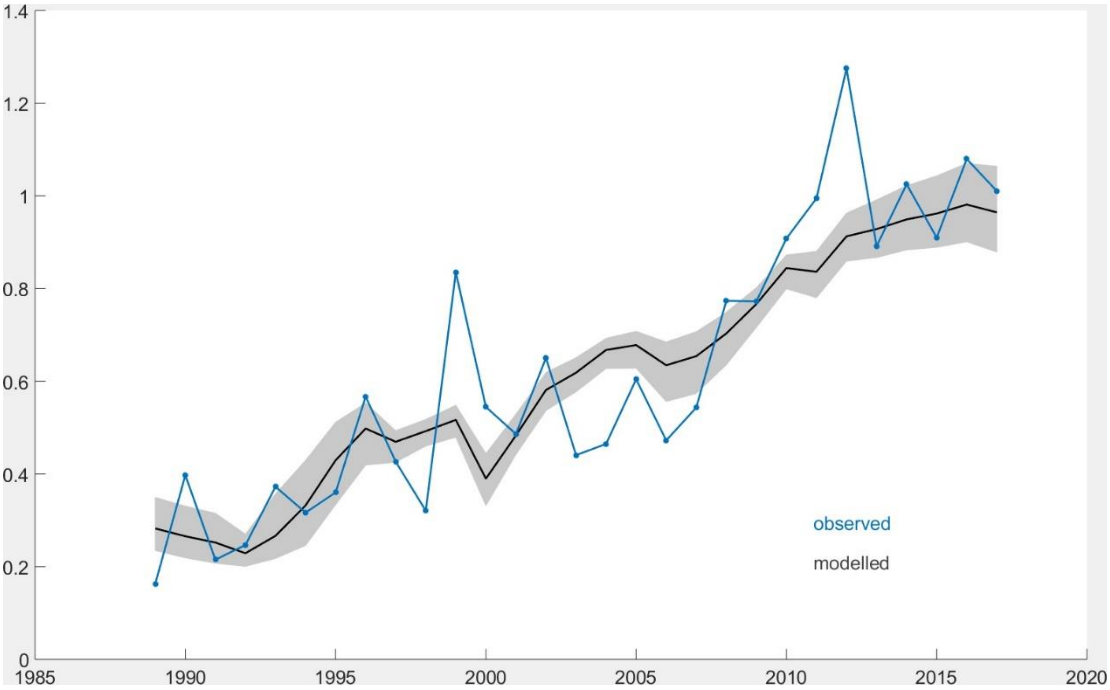


Figure 23: Northern Gulf barramundi stock standardised catch rate goodness-of-fit where the observed annual standardised catch rate is the blue line and modelled estimated is the black line.

4.2.3. Total Allowable Commercial Catch (TACC) scenarios

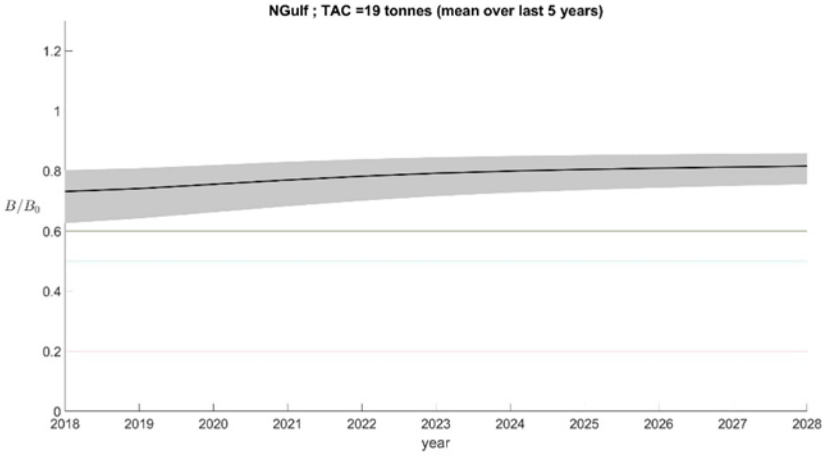
Predicted trends in exploitable biomass under five alternative constant Total Allowable Commercial Catch (TACC) scenarios were investigated.

A constant TACC of 32 tonnes (i.e., the 2017 harvest) yields a B/B_0 of 0.69 in 2027.

A TACC of 19 tonnes, the mean of the past five years, yields a relatively stable biomass ratio around 0.81. While a TACC of 15 tonnes - the mean catch over the past ten years - results in a slightly higher biomass ratio.

A TACC of 40 tonnes appears to be close to the highest level which avoids a sustained decline below the level of B/B_0 of 0.60 by 2027.

A TACC of 50 tonnes was also included but would be likely to lead to a sustained decline in exploitable biomass by 2023 below the SFS target level of B/B_0 = 0.60.



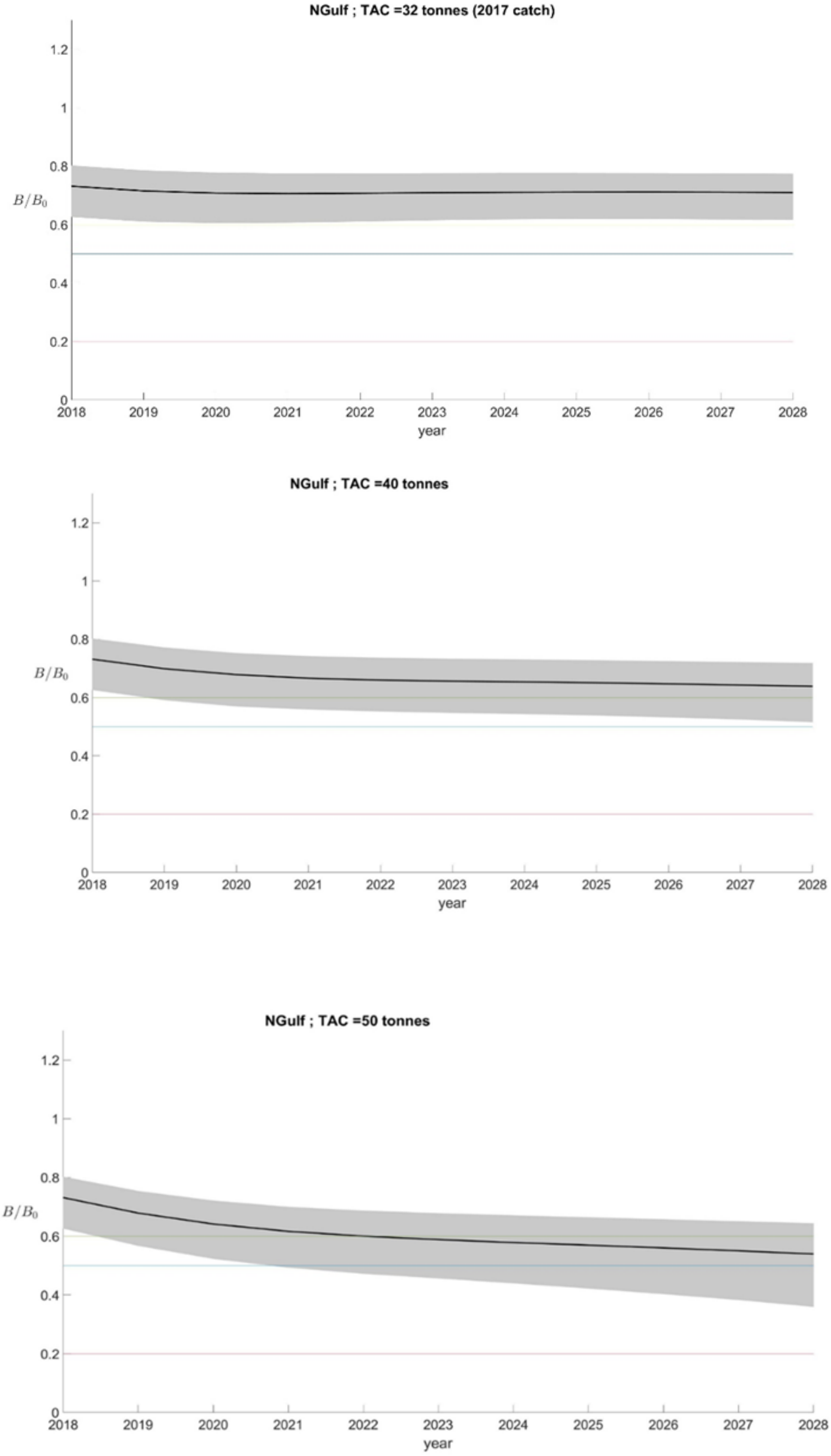


Figure 24: Northern Gulf barramundi stock modelled effects of constant Total Allowable Commercial Catch (TACC) for (a) 19 tonnes, (b) 32 tonnes, (c) 40 tonnes and (d) 50 tonnes on the projected exploitable biomass to virgin biomass ratio 2018 to 2028.

4.2.4. Sensitivity Analysis

Three different types of scenarios were investigated for sensitivity to the model assumptions. The refitted model parameter estimates, for all scenarios, are presented in Appendix F, Table 17. Stock status indicators are presented in Table 6 and Figure 26.

Sensitivity testing indicates that for the Northern Gulf barramundi stock, estimated results were somewhat sensitive to the assumed initial depletion rate ψ, relatively insensitive to a changing catchability q_{inc} but highly sensitive to the incorporation of recreational harvest scenarios. The latter is due to the estimated recreational harvest (mean of 17 tonnes, Table 1), being 2.37 times the commercial catch.

In view of the relatively low commercial catch tonnages in the Northern Gulf, the recreational harvest seems to dominate and causes major changes in the parameter estimates and model estimates (Table 17). Results for the Northern Gulf stock highlight that recreational harvest can have significant effects on model results. However, estimated recreational harvest was based on only three years of available data. Hence, we recommend that recreational fishing harvest be reported/monitored more consistently and across consecutive years to generate a time series of harvest.

It is important to note that - with the exception of the recreational harvest scenarios - in all other sensitivity scenarios for the Northern Gulf stock, there was a strong trend of recovery in both the exploitable biomass ratio B/B_0 and the egg production ratio E/E_0.

a) Initial depletion rate ($\psi_{low} = 0.1$, $\psi_{high} = 0.3$)

The sensitivity testing indicated that model results for the Northern Gulf stock are sensitive to the assumed initial depletion rate (ψ). Under the base case ($\psi = 0.2$). The exploitable biomass ratio B/B_0 of the Northern Gulf barramundi stock was estimated in 2017 at 0.73.

When the stock was assumed to be more depleted ($\psi_{low} = 0.1$ in 1989) the exploitable biomass ratio was estimated in 2017 to be 0.62; while if the stock was assumed to be less depleted ($\psi_{high} = 0.3$ in 1989) the exploitable biomass ratio was estimated in 2017 to be 0.77 (Table 6).

Similar results were observed for the egg production ratio E/E_0. If the stock was more depleted, E/E_0 was estimated in 2017 to be 0.42, which is only 68 per cent of the base case value of 0.62. If the stock was less depleted, E/E_0 was estimated in 2017 to be 0.69 (Table 6).

b) Increase in catchability (q_{inc})

In the base case model, $q_{inc} = 0$. If catchability has increased in the Northern Gulf stock, q_{inc} was estimated at 0.321, corresponding to a catchability in 2017 of 1.37 times the mean catchability over the period 1989-1993.

Under this scenario, the exploitable biomass ratio B/B_0 in 2017 was estimated to be 0.71, only slightly different to the base case estimate of 0.73.

However, the egg production ratio E/E_0 was estimated in 2017 to be 0.55, which is a 10 per cent reduction compared to estimated E/E_0 of 0.61 for the base case (Table 6).

c) Recreational harvest

For the Northern Gulf barramundi stock, there is a considerable difference in overall harvest when recreational harvest was incorporated into the assessment. The results vary, depending on the assumption used to generate a recreational harvest time series. While one scenario calculates the mean harvest for the three years of data and adds it as a constant to the commercial harvest, the other scenario calculates the mean of the per cent of recreational to commercial harvest and applies this per cent throughout the time series (i.e., 1989 to 2017).

Figure 25 illustrates the differences in the total estimated harvest (commercial and recreational combined) based on these two scenarios.

While the first scenario of a constant recreational harvest that is added to the commercial harvest in each year is indicated by the solid blue curve, the second scenario of the addition of a per cent of the commercial catch of that year is indicated by the dotted black curve.

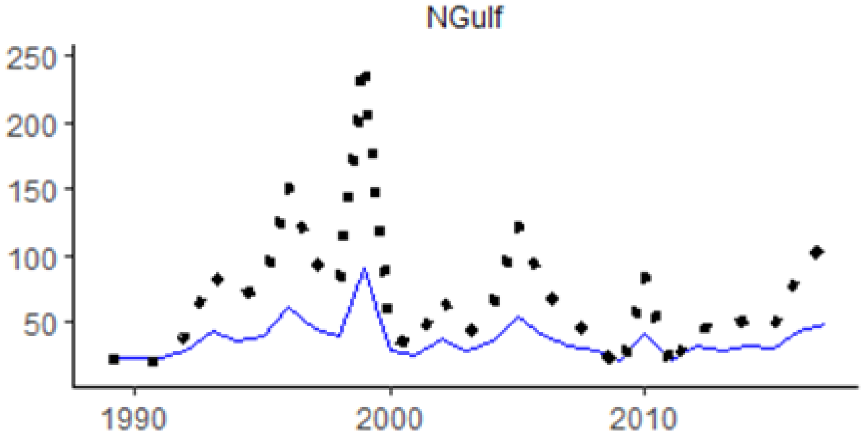


Figure 25: Northern Gulf barramundi stock estimated total harvest (commercial and recreational combined) based on two recreational harvest scenarios. The solid blue line assumes a total constant recreational harvest added to the varying commercial harvest, the dotted black line assumes a constant proportional recreational harvest added to the varying commercial harvest.

For consistency of analyses across stocks, results for a constant proportional recreational harvest scenario are included (Table 6), despite concerns about the scenario's veracity. These concerns stem from the estimate of the recreational harvest in the Northern Gulf being 2.37 times the commercial harvest. Apart from that multiple being based on only three years of data, closer examination of the raw data reveals that in 2011, the commercial total catch was only 3.77 tonnes, the lowest of the 29 years. Hence, we regard the 2.37 multiple as biased.

Given the differences illustrated in Figure 25, it is not surprising that the estimated exploitable biomass ratio B/B_0 and egg production ratio E/E_0 differ between these two scenarios (Table 6). Both scenarios of incorporating recreational harvest have a large increase in the total tonnage of barramundi harvested compared to the base case scenario (i.e., only commercial harvest), which leads to a reduction in the estimated of exploitable biomass and egg production ratios.

Under both recreational harvest scenarios, the estimated biomass ratio B/B_0 was considerably lower than in the base case (Table 6). In particular, under the first scenario, the estimated value of exploitable biomass ratio B/B_0 in 2017 was 0.52, compared to 0.73 for the base case. Under the second scenario the estimated value of exploitable biomass ratio B/B_0 in 2017 was only 0.21.

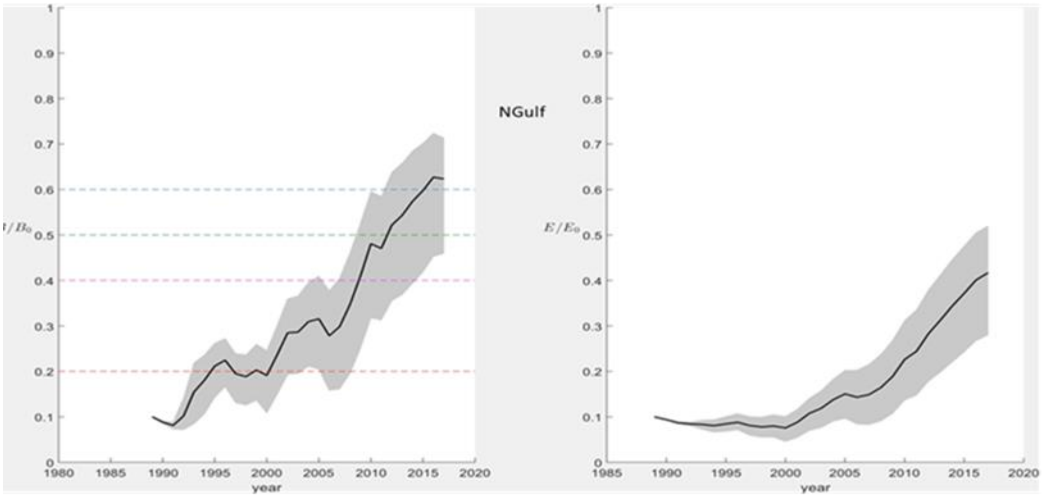
Egg production ratios E/E_0 in 2017 are similarly affected, and were estimated at 0.37 (constant harvest tonnage scenario) and 0.19 (constant harvest proportion scenario) compared to the egg production ratio of 0.61 for the base case.

We also note that under the second scenario L_∞ for the Northern Gulf barramundi stock was estimated much lower than in the base case, see Table 17 in Appendix F. The decrease in the estimated L_∞ is caused by the increased harvest that requires a larger proportion of the species to be vulnerable to fishing.

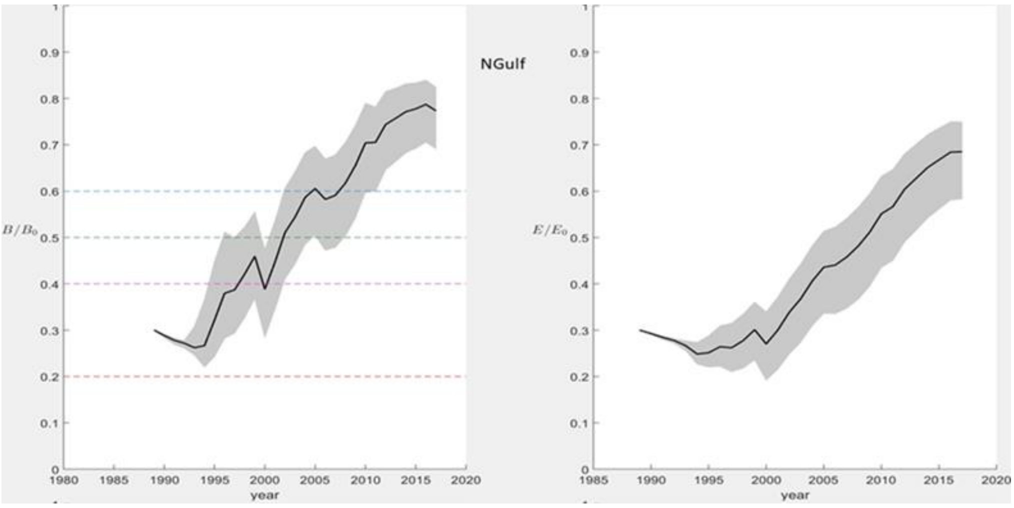
Table 6: Northern Gulf barramundi stock median values of stock status indicators (exploitable biomass to virgin biomass and egg production ratio) estimated under alternate model scenarios for select years.

Northern Gulf	1989	2005	2008	2012	2015	2017
Base case						
B/B_0	0.20	0.51	0.52	0.68	0.73	0.73
E/E_0	0.20	0.31	0.36	0.50	0.58	0.61
Sensitivity results						
B/B_0 ψ_{low}	0.10	0.32	0.35	0.52	0.60	0.62
E/E_0 ψ_{low}	0.10	0.15	0.16	0.28	0.37	0.42
B/B_0 ψ_{high}	0.30	0.61	0.62	0.74	0.78	0.77
E/E_0 ψ_{high}	0.30	0.44	0.48	0.60	0.67	0.69
B/B_0 q_{inc}	0.20	0.50	0.51	0.67	0.71	0.71
E/E_0 q_{inc}	0.20	0.28	0.31	0.44	0.52	0.55
B/B_0+ Rec con	0.20	0.30	0.31	0.44	0.49	0.52
E/E_0+ Rec con	0.20	0.17	0.18	0.27	0.33	0.37
B/B_0+ Rec prop	0.20	0.18	0.19	0.23	0.21	0.21
E/E_0+ Rec prop	0.20	0.16	0.17	0.21	0.19	0.19

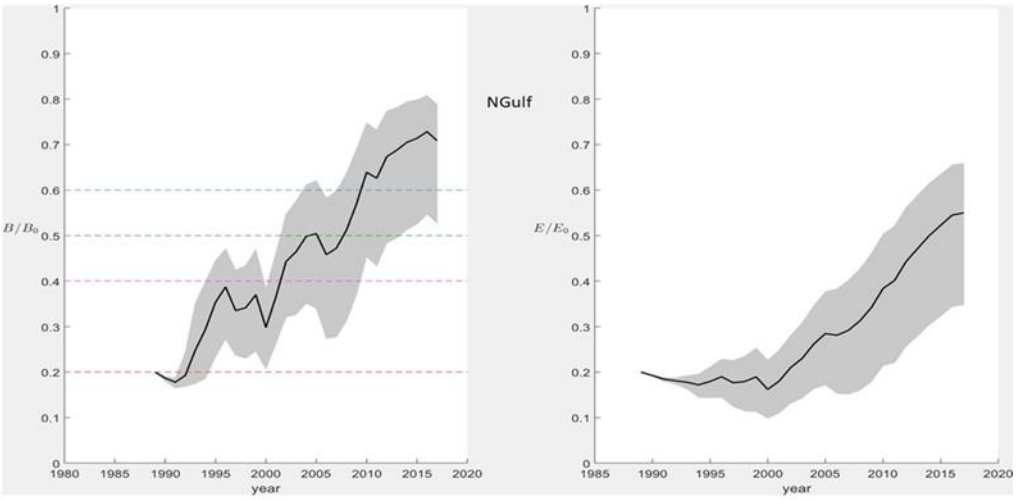
a) Greater depletion rate ($\psi_{low} = 0.1$)



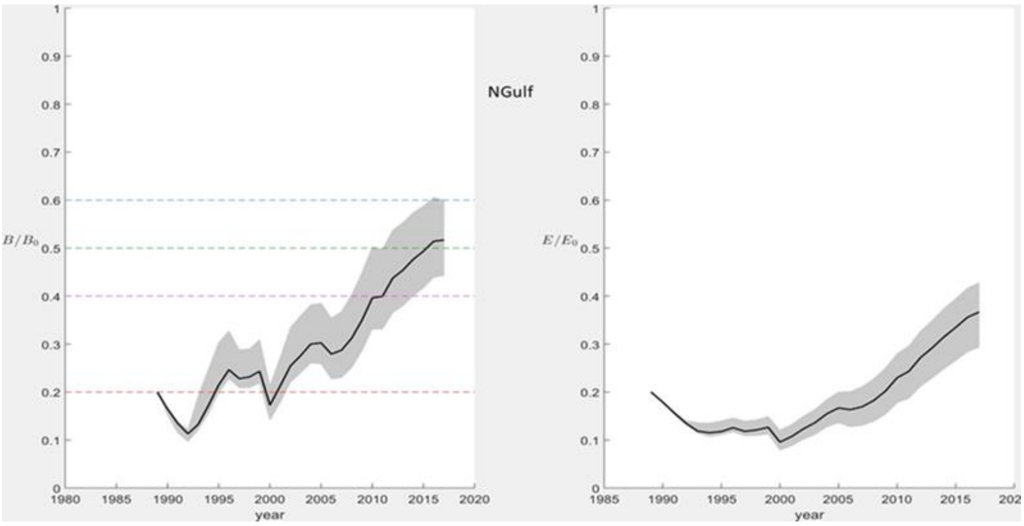
b) Lesser depletion rate ($\psi_{high} = 0.3$)



c) Increasing catchability (q_{inc})



d) Recreational harvest – addition of constant harvest = 17 tonnes



e) Recreational harvest – addition of constant proportion = 237 per cent

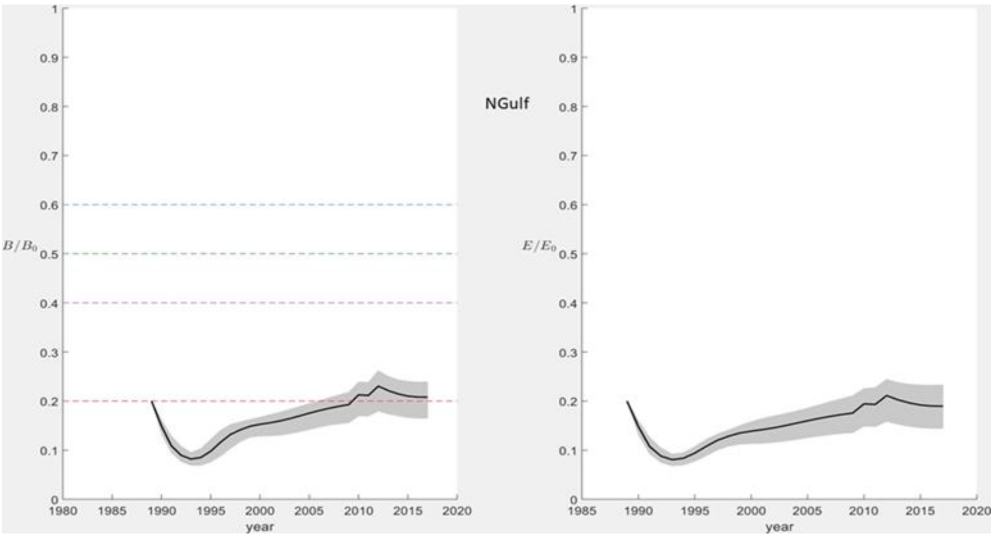


Figure 26: Sensitivity analysis of Northern Gulf barramundi stock status indicators B/B_0 and E/E_0 for (a) greater depletion, (b) lesser depletion, (c) increased catchability, (d) recreational harvest constant tonnage, and (e) recreational harvest constant proportion. The blue dashed line is the 60 per cent 2027 target of the SFS, the green dashed line is the 50 per cent biomass ratio (MSY), the pink dashed line is the 40 per cent 2020 target of the SFS and red dashed line is the 20 per cent biomass ratio (Commonwealth limit reference point).

4.3. North East Coast

4.3.1. Stock status indicator results

The stock status indicators estimated for the North East Coast barramundi stock are presented in Figure 27 and Table 7.The important features are:

- The exploitable biomass ratio B/B_0 in 2017 was estimated at 0.53.
- The initial decline in exploitable biomass and egg production ratios is the consequence of the assumed initial depletion rate of 0.25 in 1988 and an annual harvest at levels around 51 tonnes in 1988-1990 with a peak in 1991 of 92 tonnes. Under the assumption of a strong depletion in 1988, these harvest values cause a further decline in biomass and egg production levels.
- The egg production ratio E/E_0 has not recovered from the assumed initial depletion rate of 0.25 in 1988. Indeed, the model shows a period of decline followed by an upturn, in 2017, to the 0.254 level. This is of concern and should be investigated further.

We also report B/B_{msy} in Table 7 which is the exploitable biomass compared to the exploitable biomass at maximum sustainable yield (MSY), noting that B_{MSY}/B_0 is theoretically 0.5, and that for sustainability B/B_{msy} values should be at least 1.0. For the North East Coast barramundi stock, B/B_{msy} was estimated at 0.90 in 2017. Ideally, F/F_{msy} should be less than 1.0. However, for the North East Coast stock, F/F_{msy} was estimated to be greater than 1.0 for most years (Table 7), which limited the ability of the modelled barramundi population to increase its biomass.

Table 7: North East Coast barramundi stock median values of stock status indicators for selected years.

NEC	1988	1995	2000	2005	2010	2015	2017
B/B_0	0.25	0.38	0.39	0.43	0.48	0.43	0.53
E/E_0	0.25	0.19	0.21	0.19	0.20	0.21	0.25
B/B_{msy}	0.53	0.64	0.67	0.74	0.83	0.73	0.90
F/F_{msy}	0.86	1.03	1.64	1.46	1.66	1.14	0.96

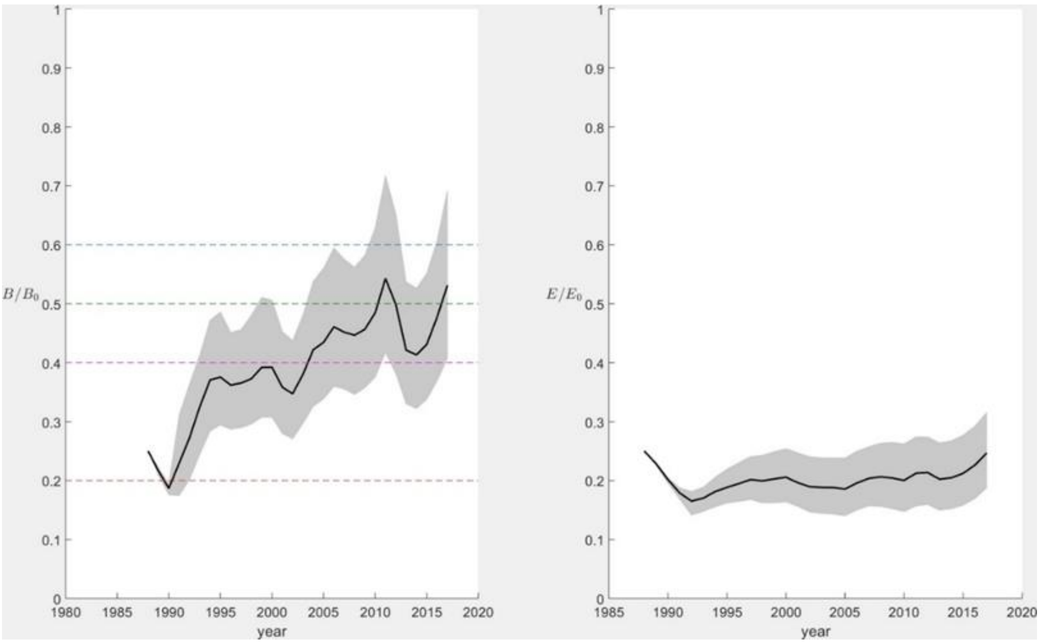


Figure 27: North East Coast barramundi stock status indicators. The blue dashed line is the 60 per cent 2027 target of the SFS, the green dashed line is the 50 per cent biomass ratio (MSY), the pink dashed line is the 40 per cent 2020 target of the SFS and red dashed line is 20 per cent biomass ratio (Commonwealth limit reference point).

4.3.2. Goodness-of-Fit

Goodness-of-fit to the annual standardised catch rates for the North East Coast stock (see Appendix C) are displayed in Figure 28. For the NEC stock, the population model replicates very well the patterns in the standardised catch rate.

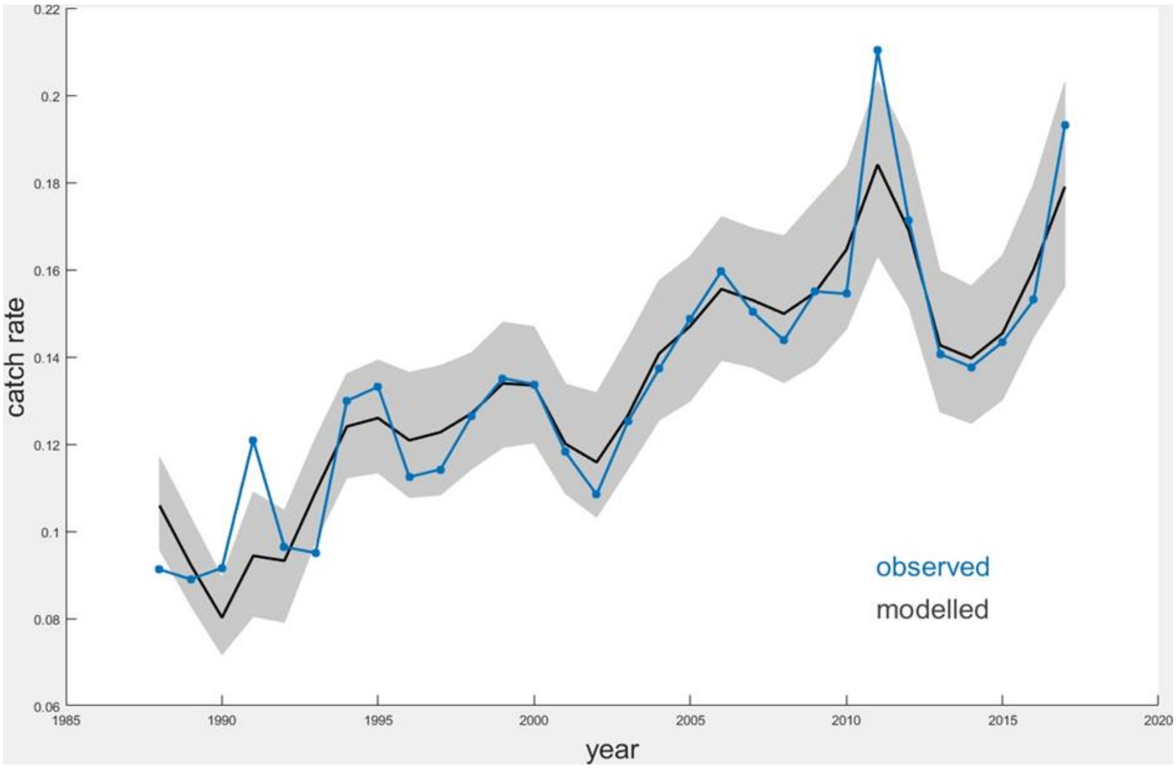


Figure 28: North East Coast barramundi stock standardised catch rate goodness-of-fit where the observed annual standardised catch rate is the blue line and modelled estimated is the black line.

Goodness-of-fit to the Fishery Monitoring age-frequency data for 2007 to 2017 are displayed in Figure 29. This figure indicates that the population model replicates some but not all of the patterns in the age-frequency data. For further discussion on variation in age-frequency proportions see Section 4.6.

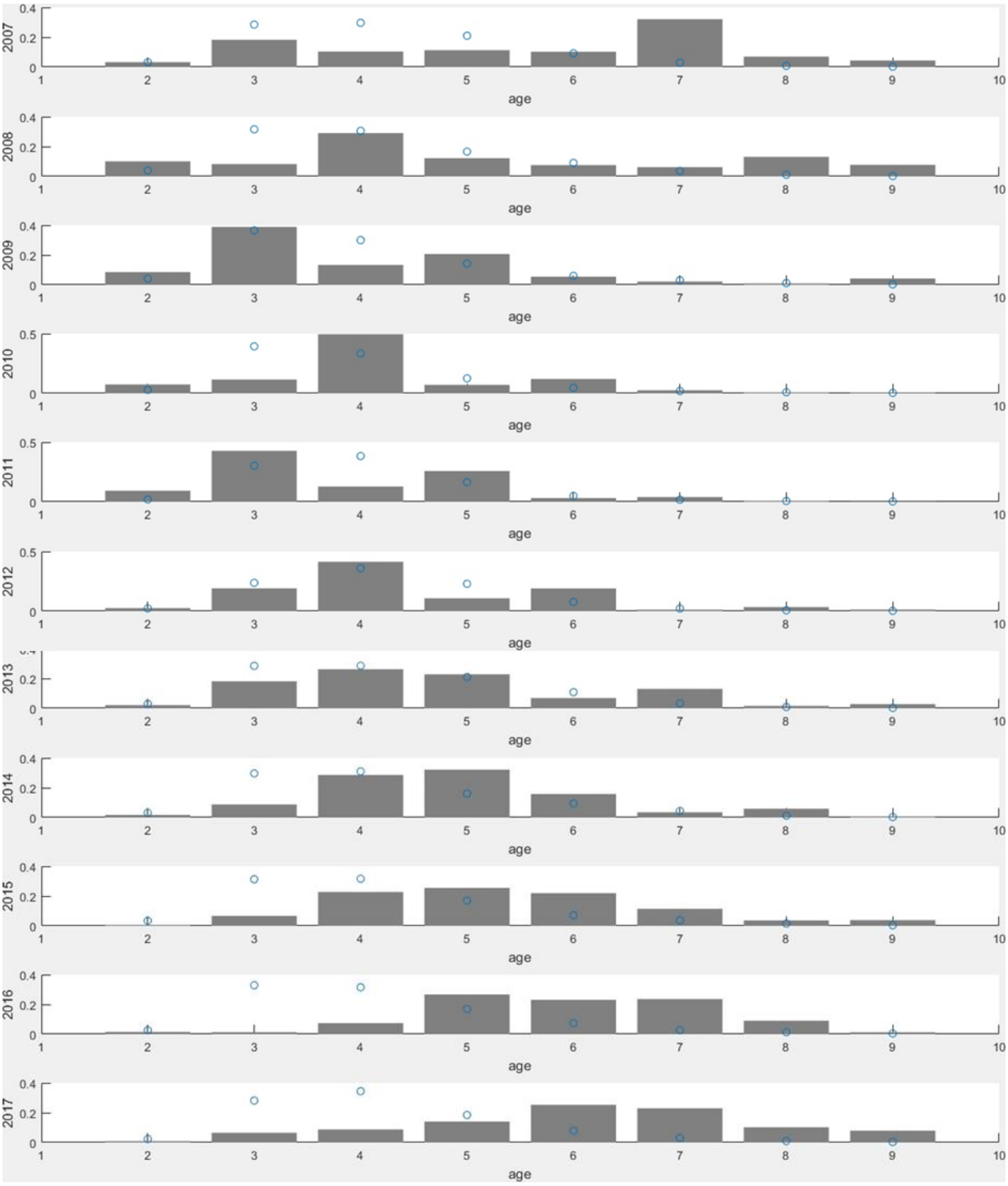


Figure 29: North East Coast barramundi stock age-frequency goodness-of-fit where observed data are the bars and modelled estimated are the circles. Note the change in y-axis scale between years.

4.3.3. Total Allowable Commercial Catch (TACC) Scenarios

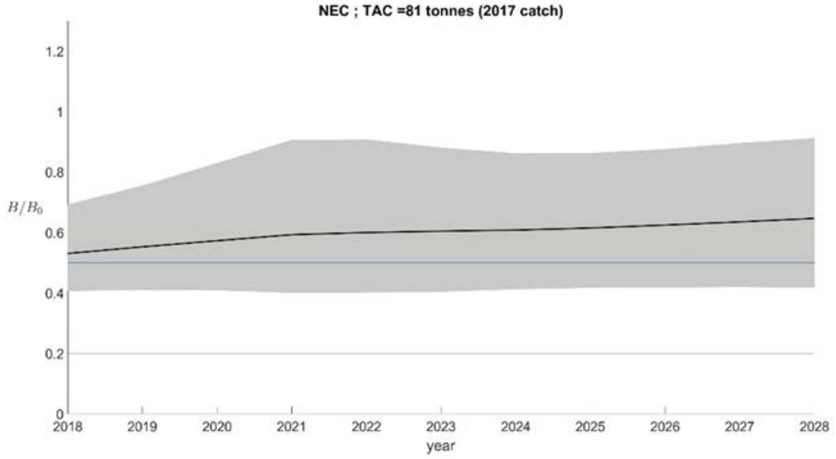
Predicted trends in exploitable biomass under four alternate constant Total Allowable Commercial Catch (TACC) scenarios are presented in Figure 30.

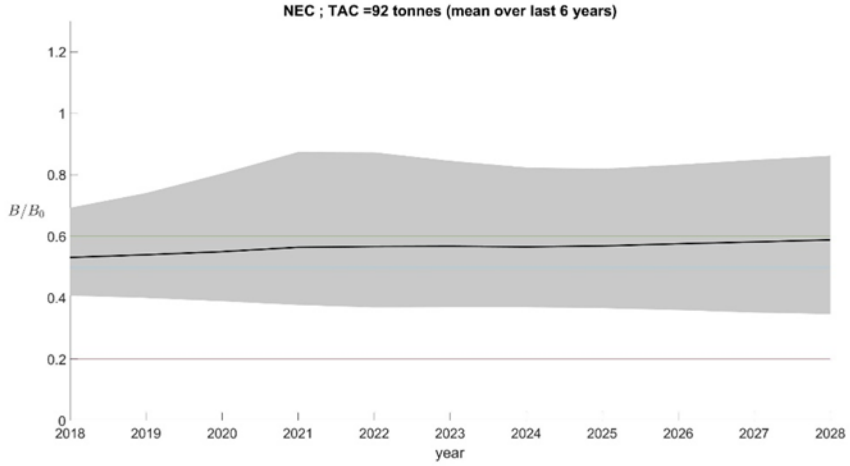
Continuing to catch 81 tonnes (i.e., the catch in 2017 and the average of the past five years) yields an increase in the biomass ratio B/B_0 to around 0.64 by 2027.

A constant TACC of 92 tonnes, the average of the past six years, yields a biomass ratio B/B_0 of 0.58 in 2027.

The 10 year average, 110 tonnes if harvested as the constant TACC, yields a biomass ratio B/B_0 that is slightly below 0.5 (MSY) by 2023.

A TACC of 125 tonnes yields a biomass ratio B/B_0 below 0.5 (i.e., B_{MSY}/B_0) by 2020.





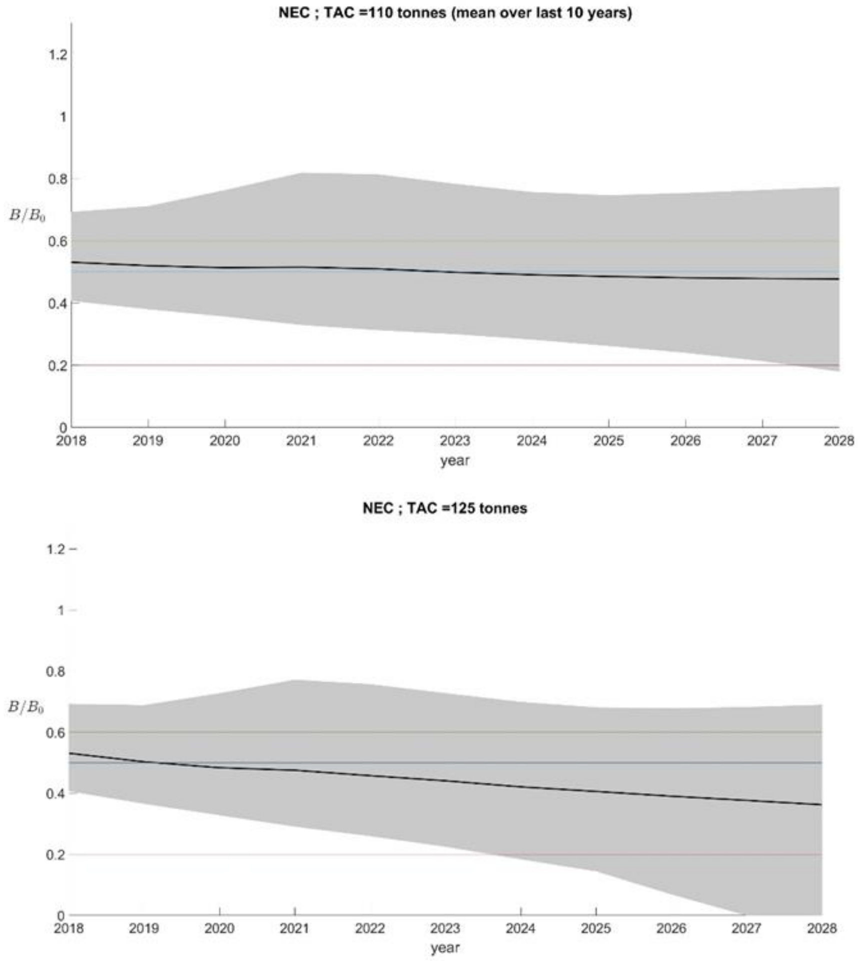


Figure 30: North East Coast barramundi stock modelled effects of constant Total Allowable Commercial Catches (TACC) for (a) 81 tonnes, (b) 92 tonnes, (c) 110 tonnes and (d) 125 tonnes on the projected exploitable biomass to virgin biomass ratio 2018 to 2028.

4.3.4. Sensitivity Analysis

Three different types of scenarios were investigated for sensitivity to the model assumptions. The refitted model parameter estimates, for all scenarios, are presented in Appendix F, Table 18. Stock status indicators are presented in Table 8 and illustrated in Figure 32.

Sensitivity testing indicates that for the North East Coast stock, estimated results were most sensitive to the assumed initial depletion level, with all scenarios suggesting limited recovery from 1988 levels.

Model results for the NEC stock were also sensitive to recreational harvest scenarios. The biomass ratio B/B_0 was reduced from 0.53 in the base case to 0.43 and 0.45 considering a constant recreational harvest or a proportional recreational harvest respectively. More significant was the change in the egg production ratio E/E_0, that was estimated in 2017 to be 0.07 or 0.19, respectively, compared to 0.25 for the base case (Table 8).

a) Initial depletion rate ($\psi_{low} = 0.1$, $\psi_{high} = 0.3$)

Under the base case scenario of $\psi = 0.25$, the biomass ratio B/B_0 of the North East Coast barramundi stock was estimated in 2017 to be 0.53.

When the stock was assumed to be more depleted ($\psi_{low} = 0.15$ in 1988), the exploitable biomass ratio B/B_0 was estimated in 2017 to be 0.33; while if the stock was assumed to be less depleted ($\psi_{high} = 0.35$), the exploitable biomass ratio B/B_0 was estimated in 2017 to be 0.71 (Table 8).

Similar results were observed for the egg production ratio E/E_0. If the NEC stock was more depleted, E/E_0 was estimated in 2017 to be 0.13 compared to 0.25 for the base case. If the stock was less depleted, E/E_0 was estimated to be 0.38 (Table 8).

b) Increase in catchability (q_{inc})

For the NEC stock, the catchability parameter (q_{inc}) was estimated to be 0.11, which corresponds to an increase in catchability to 1.11 times the catchability in of years 1988-1992. Given this relatively shallow increase in catchability, it is not surprising that the estimated ratio of exploitable biomass and egg production were relatively similar to that estimated in the base case.

The exploitable biomass ratio B/B_0 in 2017 was estimated to be 0.51 compared to 0.53 in the base case. Similarly, the egg production ratio E/E_0 was estimated to be 0.21 compared to 0.25 in the base case.

c) Recreational harvest

For the North East Coast barramundi stock, recreational harvest was estimated to be about 70 per cent of the commercial harvest (Table 1). Under both scenarios incorporating recreational harvest, the exploitable biomass ratio B/B_0 was estimated slightly lower than the base case.

If a constant tonnage of recreational harvest was incorporated (i.e., 74 tonnes per year), the exploitable biomass ratio B/B_0 was estimated in 2017 to be 0.43, compared to the base case estimate of 0.53.

If a constant proportional recreational harvest was incorporated (i.e., 67 per cent of the commercial harvest per year), the estimated exploitable biomass ratio in 2017 is 0.45, which is similar to the base case.

The incorporation of recreational harvest in the NEC barramundi stock assessment model has a notable effect on the egg production ratio E/E_0. Considering a constant recreational harvest of 74 tonnes per year, the egg production ratio in 2017 drops drastically to 0.07 compared to 0.25 in the base case. If considering a constant proportional recreational harvest of 67 per cent of commercial harvest, the egg production ratio in 2017is at 0.19.

These results reflect the effects on B/B_0 and E/E_0 of the quite different total harvest curves (Figure 31). This highlights again the importance of having good estimates of annual harvest over time of all sectors that take barramundi.

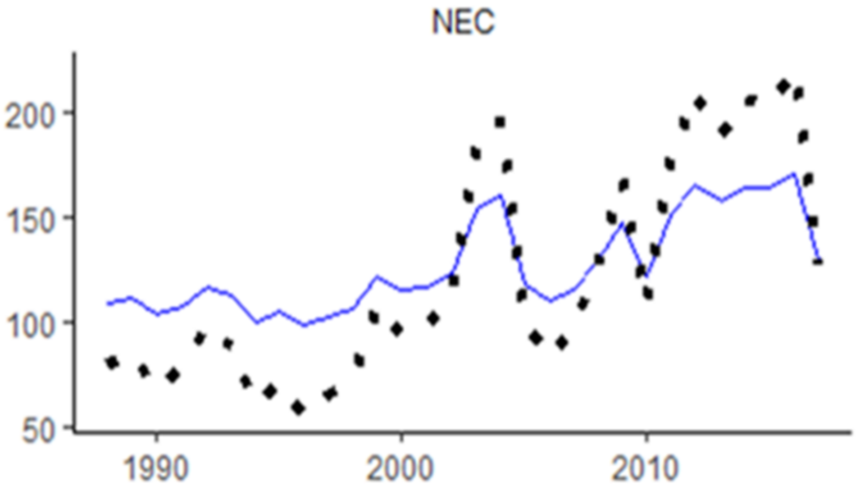
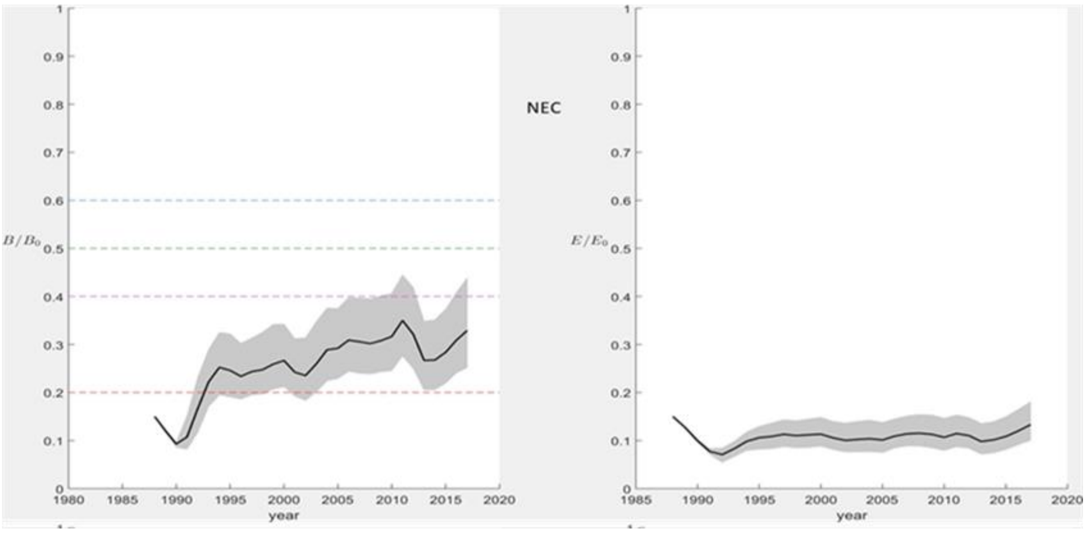


Figure 31: North East Coast barramundi total harvest estimates (commercial and recreational combined). The solid blue line assumes a total harvest (commercial + 74 tonne recreational), the dotted black line assumes a proportional harvest (commercial + 67 per cent of commercial for recreational).

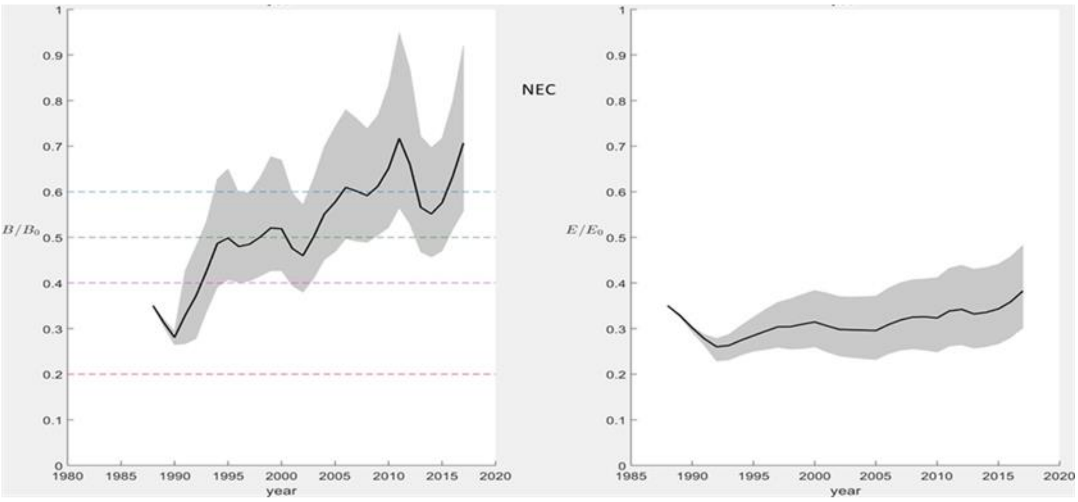
Table 8: North East Coast barramundi stock median values of stock status indicators (exploitable biomass to virgin biomass and egg production ratio) estimated under alternate model scenarios for selected years.

NEC	1988	2005	2008	2012	2015	2017
Base case						
B/B_0	0.25	0.43	0.45	0.50	0.43	0.53
E/E_0	0.25	0.19	0.21	0.21	0.21	0.25
Sensitivity results						
$B/B_0\Psi_{\mathrm{low}}$	0.15	0.29	0.30	0.32	0.28	0.33
$E/E_0\ \Psi_{\mathrm{low}}$	0.15	0.10	0.12	0.11	0.11	0.13
$B/B_0\psi_{\mathrm{high}}$	0.35	0.58	0.59	0.66	0.58	0.71
$E/E_0\ \psi_{\mathrm{high}}$	0.35	0.30	0.33	0.34	0.34	0.38
$B/B_0\ q_{inc}$	0.25	0.44	0.44	0.49	0.41	0.51
$E/E_0\ q_{inc}$	0.25	0.17	0.19	0.19	0.18	0.21
B/B_0+ Rec con	0.25	0.40	0.40	0.44	0.38	0.43
E/E_0+ Rec con	0.25	0.06	0.06	0.07	0.07	0.07
B/B_0+ Rec prop	0.25	0.40	0.42	0.45	0.39	0.45
E/E_0+ Rec prop	0.25	0.14	0.17	0.16	0.16	0.19

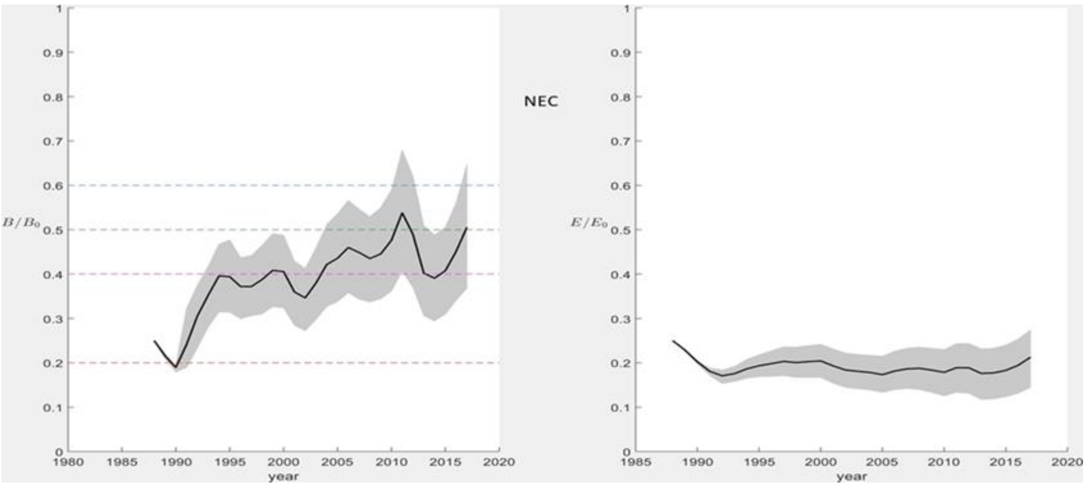
a) Greater depletion rate (ψ_{low}=0.15)



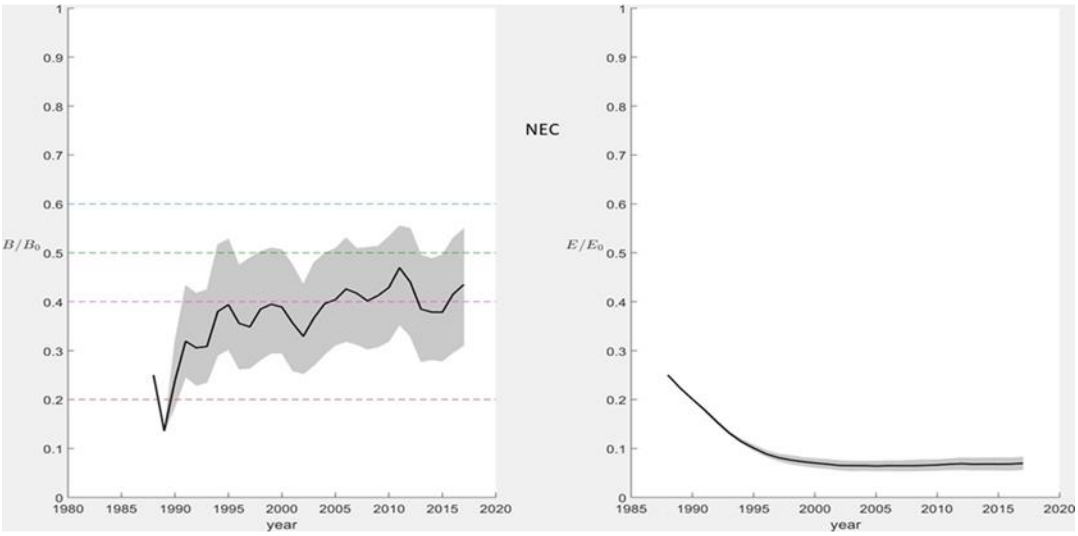
b) Lesser depletion rate (ψ_{high}= 0.35)



c) Increasing catchability (q_{inc})



d) Recreational harvest – addition of constant harvest = 74 tonnes



e) Recreational harvest – addition of constant proportion = 67 per cent

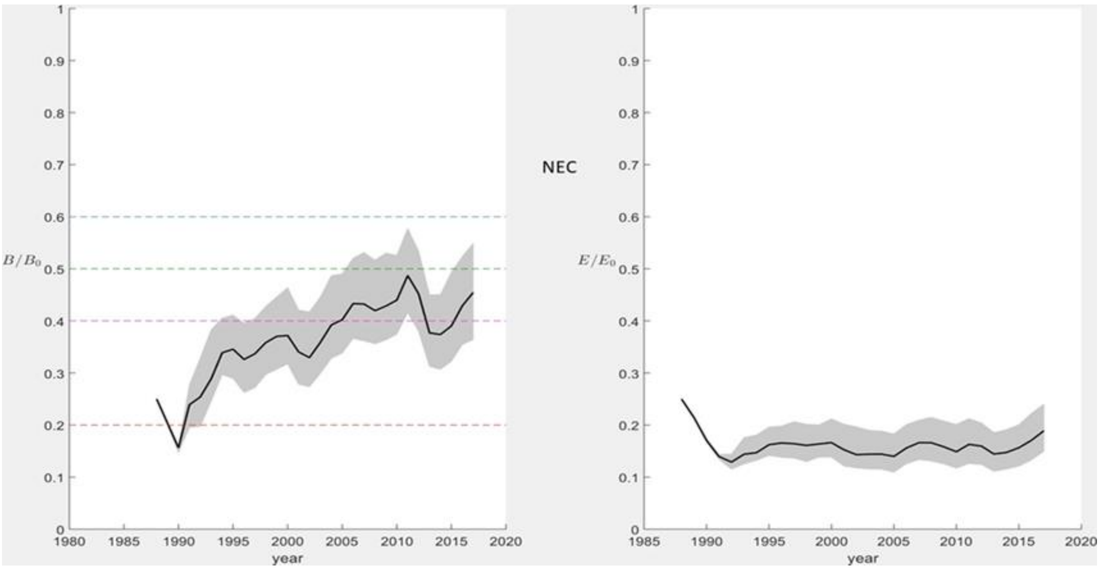


Figure 32: Sensitivity analysis of North East Coast barramundi stock status indicators B/B_0 *and* E/E_0 *for (a) greater depletion, (b) lesser depletion, (c) increased catchability, (d) recreational harvest constant tonnage, and (e) recreational harvest constant proportion. The blue dashed line is the 60 per cent 2027 target of the SFS, the green dashed line is 50 the per cent biomass ratio (MSY), the pink dashed line is the 40 per cent 2020 target of the SFS and red dashed line is 20 per cent biomass ratio (Commonwealth limit reference point).*

4.4. Mackay

For the Mackay stock, the model was calibrated using the Mackay annual standardised catch rate and the age-frequency data for the NEC stock, since there was no age-frequency data available for the Mackay stock. This assumes that the age-frequencies for the Mackay barramundi stock is similar over time to the adjacent NEC stock. The simulated stock status indicators for the Mackay barramundi stock are presented in Figure 33 and Table 9.

4.4.1. Stock status indicator results

The exploitable biomass ratio B/B_0 in 2017 for the Mackay stock was estimated to be 0.59.

The initial decline in biomass and egg production ratios is the consequence of the assumed initial depletion rate of 0.25 in 1988 as well as the non-decreasing annual catch in the first two years (Figure 2).

Patterns in the fishing pressure are similar to the other stocks, but the exploitable biomass of the Mackay stock recovers more rapidly than others. This is partially due to the fishing pressure remaining at relatively low levels in the Mackay stock with respect to F_{msy} (Table 9). This allows the stock to reach an exploitable biomass above that at maximum sustainable yield, (i.e., B/B_{msy} =1.20 in 2017, Table 9).

The Mackay stock shows an increasing trend in the exploitable biomass and egg production ratio between 1995 and 2010 (Figure 33) then a decline in the last five years. This pattern was not observed in the other barramundi stocks of the Queensland east coast (i.e., NEC or CEC). The recent downward trends in B/B_0 and E/E_0 should be monitored in the near future, especially as the catch has been relatively high with more than 75 tonnes harvested annually from this stock from 2011 to 2016.

Table 9: Mackay barramundi stock median values of stock status indicators for selected years.

Mackay	1988	1995	2000	2005	2010	2015	2017
B/B_0	0.25	0.42	0.57	0.59	0.67	0.62	0.59
E/E_0	0.25	0.23	0.39	0.43	0.50	0.46	0.43
B/B_{msy}	0.72	0.89	1.15	1.18	1.36	1.25	1.20
F/F_{msy}	0.57	0.43	0.43	0.45	0.42	0.86	0.55

In Figure 33, we observe a steep biomass ratio increase between 1992 and 2000. This is driven by two factors. One is the increase in the egg production which, in turn, supports further increase in the exploitable biomass. The other is the series of high catch rates reported in the Mackay stock for the years after 2010 (Figure 3). These high catch rates force the modelled estimates of exploitable biomass steeply upwards to achieve a compromise in the overall fit. Figure 34 shows the modelled catch rate compensating for high oscillations in the observed data.

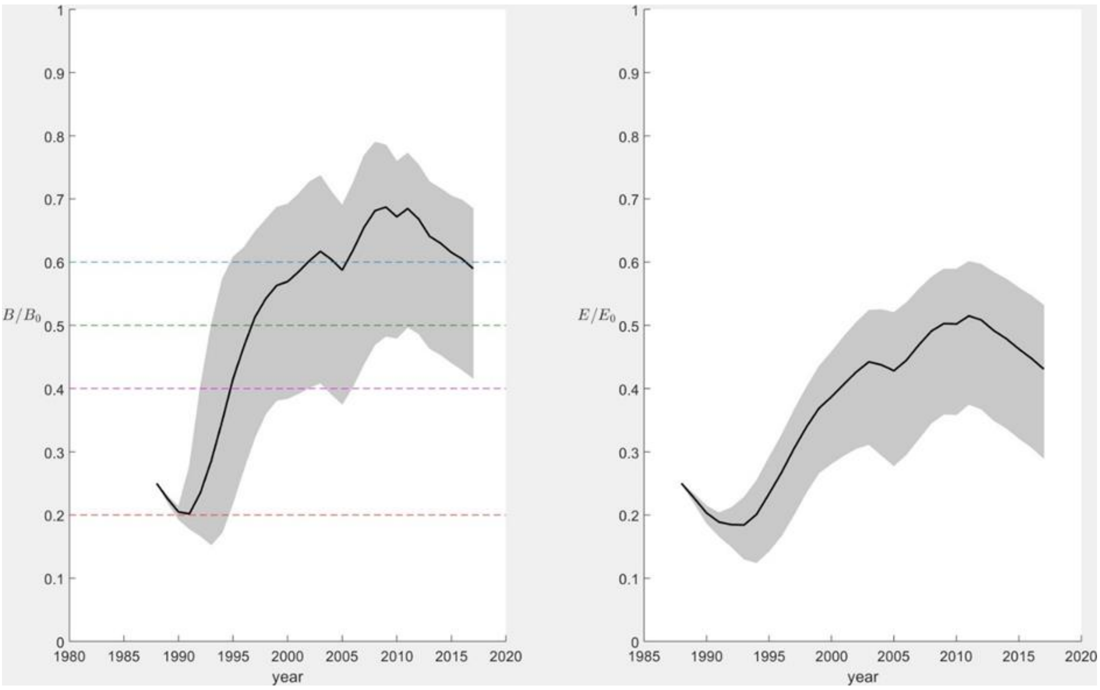


Figure 33: Mackay barramundi stock status indicators. The blue dashed line is the 60 per cent 2027 target of the SFS, the green dashed line is 50 per cent biomass ratio (MSY), the pink dashed line is the 40 per cent 2020 target of the SFS and red dashed line is the 20 per cent biomass ratio (Commonwealth limit reference point).

4.4.2. Goodness-of-Fit

Goodness-of-fit to the annual standardised catch rate data (see Appendix C) are displayed in Figure 34. For the Mackay stock, the population model only partially captures the patterns in the standardised catch rate. Note that from 1997 to 2009 the model over estimates the observed catch rates and from 2011 to 2017 it under estimates them.

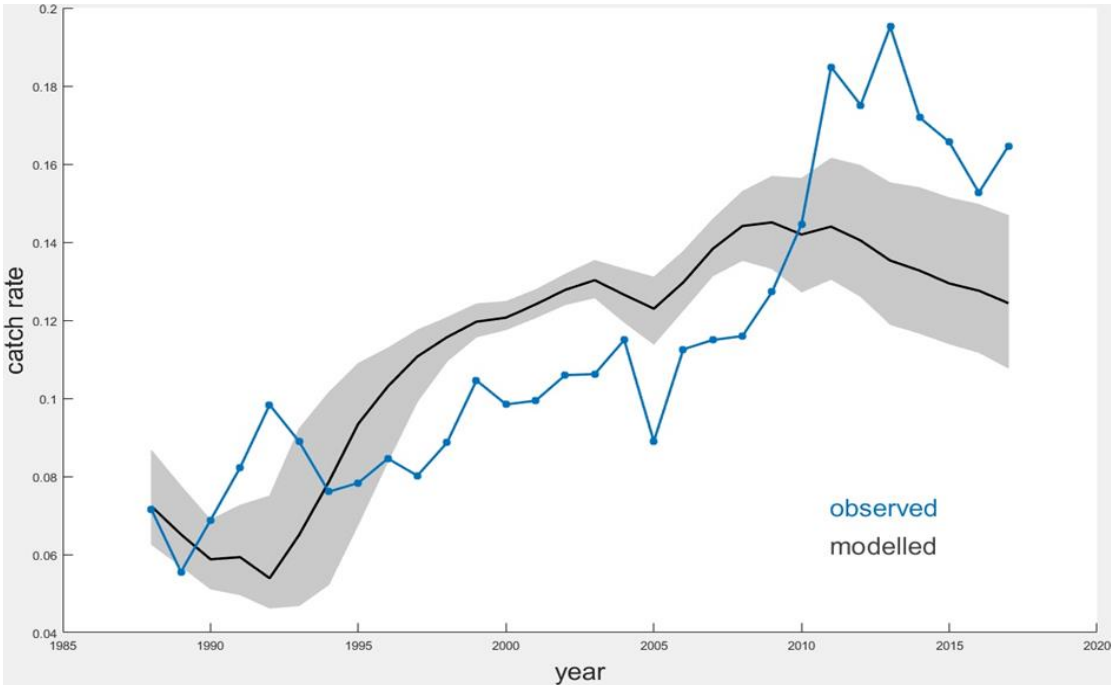


Figure 34: Mackay barramundi standardised catch rate goodness of fit where the observed annual standardised catch rate is the blue line and modelled estimated is the black line.

Goodness-of-fit to the Fishery monitoring age-frequency data (assumed to be representative for the Mackay stock) for 2007 to 2017 are given in Figure 35.

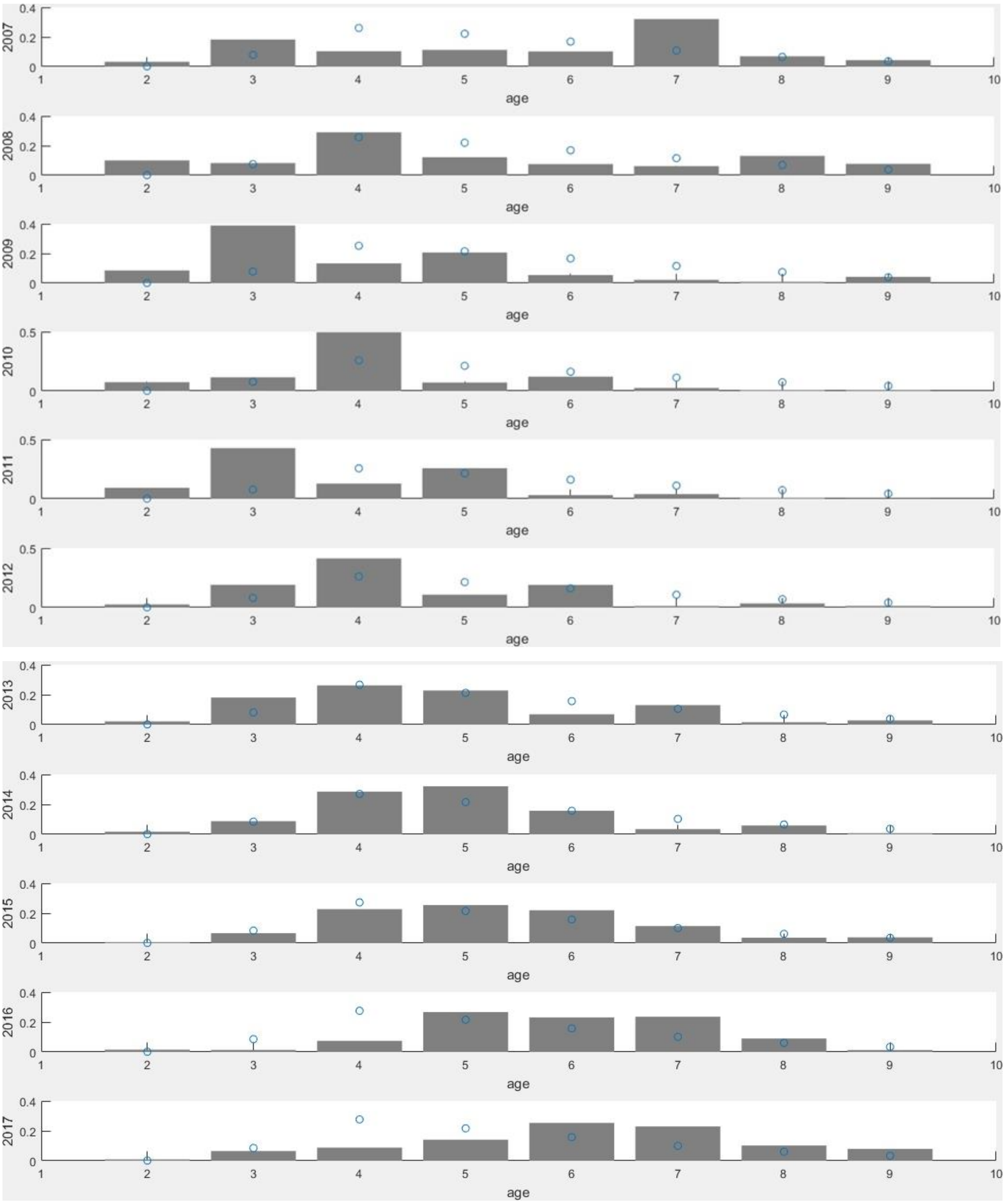


Figure 35: Mackay barramundi stock age-frequency goodness-of-fit where observed data[5] are the bars and modelled estimated are the circles.

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[5] Age-frequency data for Mackay stock was assumed to be similar to the NEC stock.

4.4.3. Total Allowable Commercial Catch (TACC) Scenarios

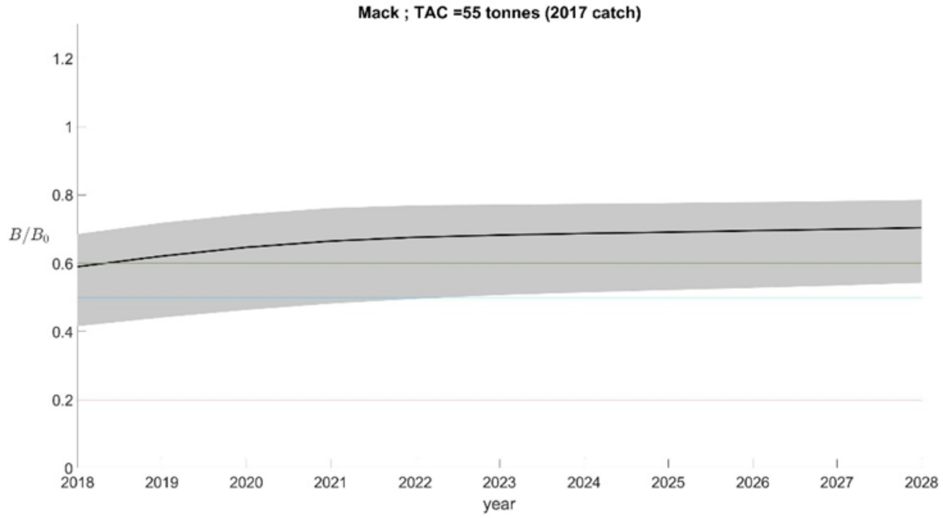
Predicted trends in the exploitable biomass ratio B/B_0 under four alternate constant total annual commercial catch (TACC) scenarios were investigated.

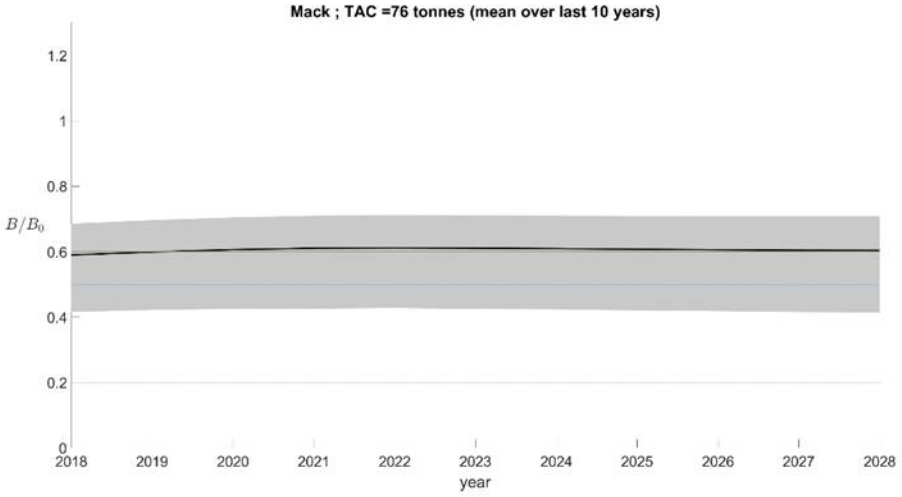
Continuing to catch 55 tonnes (i.e., the catch in 2017) yields an increase in biomass to around 0.68 by 2027.

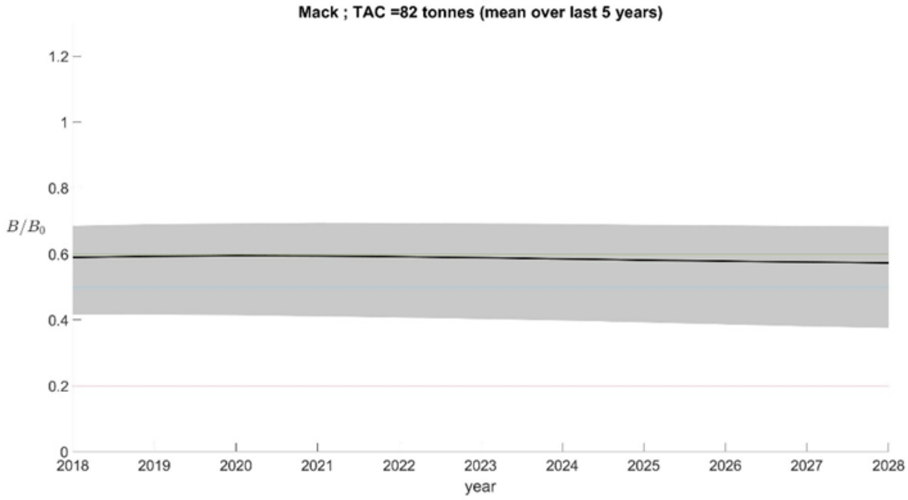
A constant TACC of 76 tonnes, the average of the past 10 years, yields an exploitable biomass ratio of 0.6 in 2027.

A TACC of 82 tonnes (the average of the past five years), if harvested each year, yields an exploitable biomass ratio that is around 0.57 by 2027.

A TACC of 96 tonnes yields an exploitable biomass ratio below the 0.5 by 2027.







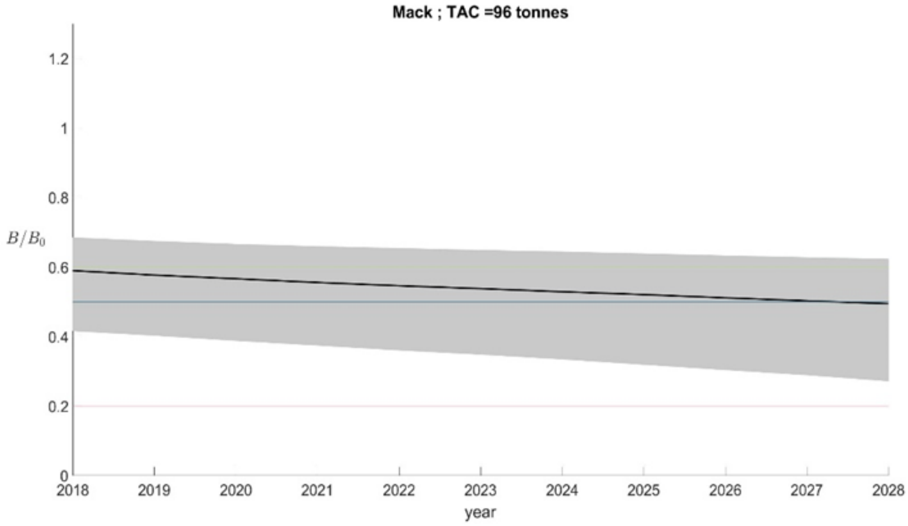


Figure 36: Mackay barramundi stock modelled effects of constant Total Allowable Commercial Catch (TACC) for (a) 55 tonnes, (b) 76 tonnes, (c) 82 tonnes and (d) 96 tonnes on the projected exploitable biomass to virgin biomass ratio 2018 to 2028.

4.4.4. Sensitivity Analysis

Three different types of scenarios were investigated for sensitivity to the model assumptions. The refitted model parameter estimates, for all scenarios, are presented in Appendix F, Table 19. Stock status indicators are presented in Table 10 and Figure 38.

All scenarios suggest for the Mackay barramundi stock a recovery in the egg production ratio E/E_0 to >0.3. In the base case, the estimated egg production ratio E/E_0 in 2017 was 0.43.

With a relatively low estimated recreational harvest (mean of 21 tonnes per year amounting to about 37 per cent of the commercial catch) model results for the Mackay stock were rather insensitive to the incorporation of recreational harvest.

However, estimated results for the Mackay stock were sensitive to an increasing catchability.

a) **Initial depletion rate (**$\psi_{low} = 0.15$, $\psi_{high} = 0.35$)

Consistent with other stocks, the assumption of a greater depletion rate led to lower biomass and egg production ratios, while a lesser depletion rate yields to higher values of these ratios.

Under the base case of $\psi = 0.25$, the Mackay barramundi stock was estimated to have an exploitable biomass ratio B/B_0 in 2017 of 0.59. When the stock was assumed to be more depleted (i.e., $\psi_{low} = 0.15$), the exploitable biomass ratio was estimated in 2017 to be 0.52; while if the stock was assumed to be less depleted ($\psi_{high} = 0.35$), the exploitable biomass ratio B/B_0 was estimated in 2017 to be 0.60.

Compared to all other stocks, the estimated exploitable biomass ratio and egg production ratio for the Mackay stock in all depletion scenarios yielded values within a narrow range (i.e., 0.52 to 0.60).

An important observation is that under the assumption of a less depleted stock (ψ_{high}), the model estimated value of L_∞ was 1097 mm (with k = 0.156, a_0=-0.32), and results in a more shallow growth curve than estimated for the base case, see Table 15 and Table 19 in Appendix F. The consequence of a more shallow growth curve is that age-classes are vulnerable to fishing mortality for a longer time (via size selectivity and the maximum size limit). This in turn reduces the number of surviving large fish (predominately female) and thus reduces the reproduction rate resulting in reduced population recovery. This is why the exploitable biomass ratio B/B_0 for the case of a lesser depletion rate (ψ_{high}) is only slightly higher than in the base case (i.e., 0.60 compared to 0.59).

b) Increase in catchability (q_{inc})

For the Mackay barramundi stock, q_{inc} was estimated at 0.663, corresponding to a catchability in 2017 that is 1.94 times the catchability during 1988-1992. This is the highest estimated increase in catchability among the stocks assessed. The increase in catchability yields a reduction in the biomass ratio B/B_o and the egg production ratio E/E_0.

For an increasing catchability, the exploitable biomass ratio B/B_0 was estimated in 2017 to be 0.46 compared to 0.59 for the base case. Similarly, the egg production ratio E/E_0 was estimated in 2017 to be 0.26, compared to the estimated E/E_0 0.43 in the base case.

c) Recreational harvest

For the Mackay barramundi stock, the recreational harvest was estimated to average 21 tonnes per year or about 37 per cent of the commercial harvest (Table 1). Although this per cent is not as large as for the Northern Gulf and the North East Coast stock, it is higher than for the Central East Coast and the Southern Gulf. Hence, the biomass ratio and egg production ratio will be effected by the inclusion of recreational harvest, being slightly lower than for the base case. The estimated total barramundi harvest (commercial and recreational combined) is similar regardless of the method used to estimate recreational harvest (Figure 37). This suggests that the estimated model ratios should yield similar results.

Incorporating recreational harvest reduced the estimated exploitable biomass ratio B/B_0 to 0.48 and 0.47 respectively, compared to 0.59 for the base case (Table 10). Egg production ratios were similarly affected, with E/E_0 estimated to be 0.33 (for both scenarios) in 2017 compared to 0.43 for the base case.

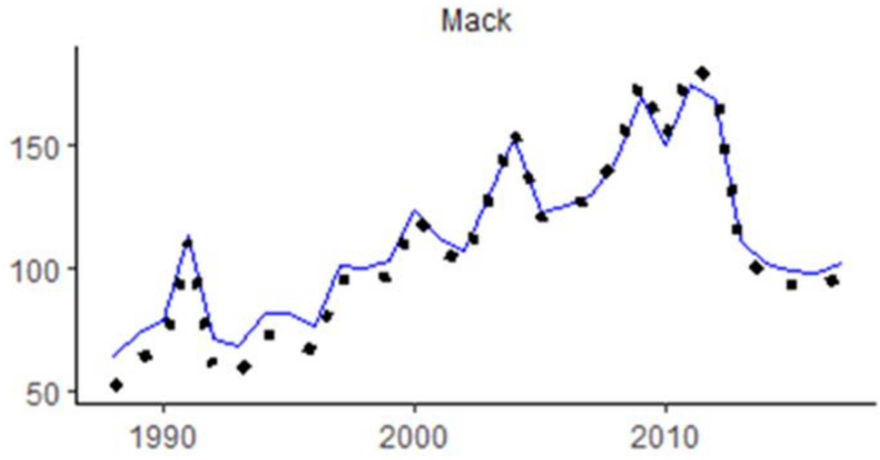
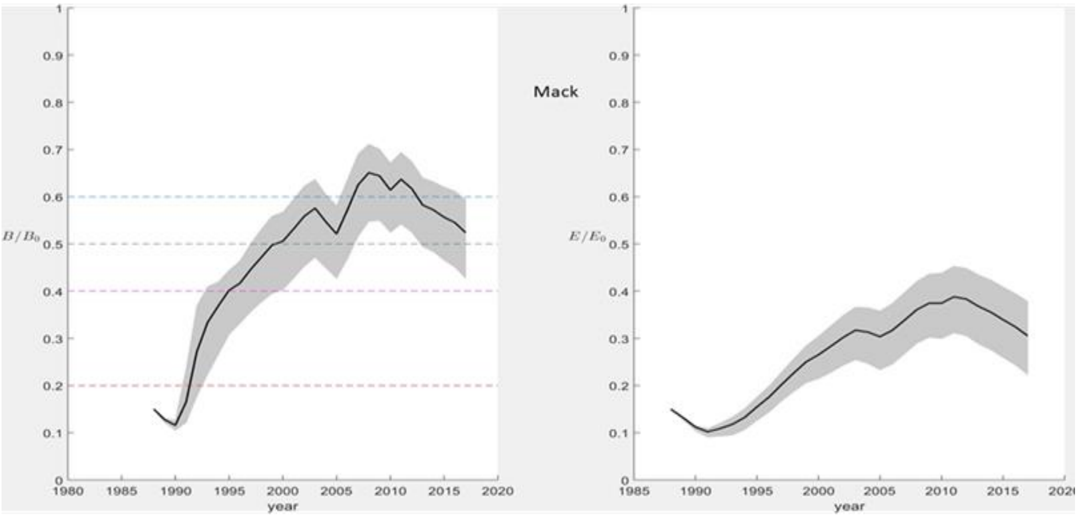


Figure 37: Mackay barramundi total harvest estimates (commercial and recreational combined). The solid blue line assumes a total harvest (commercial + 21 tonne recreational), the dotted black line assumes a proportional harvest (commercial + 37 per cent of commercial for recreational).

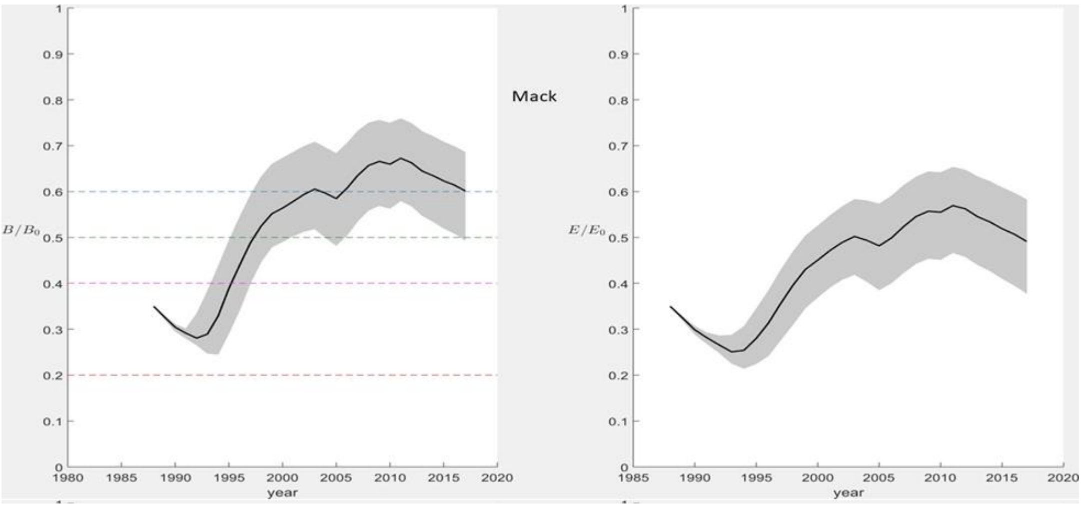
Table 10: Mackay barramundi stock median values of stock status indicators (exploitable biomass to virgin biomass and egg production ratio) estimated under alternate model scenarios for selected years.

Mackay	1988	2005	2008	2012	2015	2017
			Base case			
B/B_0	0.25	0.59	0.68	0.67	0.62	0.59
E/E_0	0.25	0.43	0.49	0.51	0.46	0.43
			Sensitivity results			
$B/B_0\psi_{\mathrm{low}}$	0.15	0.52	0.65	0.62	0.56	0.52
$E/E_0\ \psi_{\mathrm{low}}$	0.15	0.30	0.36	0.38	0.34	0.31
$B/B_0\ \psi_{\mathrm{high}}$	0.35	0.58	0.66	0.66	0.62	0.60
$E/E_0\ \psi_{\mathrm{high}}$	0.35	0.48	0.55	0.56	0.52	0.49
$B/B_0\ q_{inc}$	0.25	0.58	0.72	0.63	0.52	0.46
$E/E_0\ q_{inc}$	0.25	0.40	0.41	0.39	0.32	0.26
B/B_0+Rec con	0.25	0.45	0.53	0.54	0.50	0.48
E/E_0+Rec con	0.25	0.30	0.36	0.39	0.36	0.33
B/B_0+ Rec prop	0.25	0.47	0.56	0.56	0.50	0.47
E/E_0+Rec prop	0.25	0.34	0.41	0.42	0.36	0.33

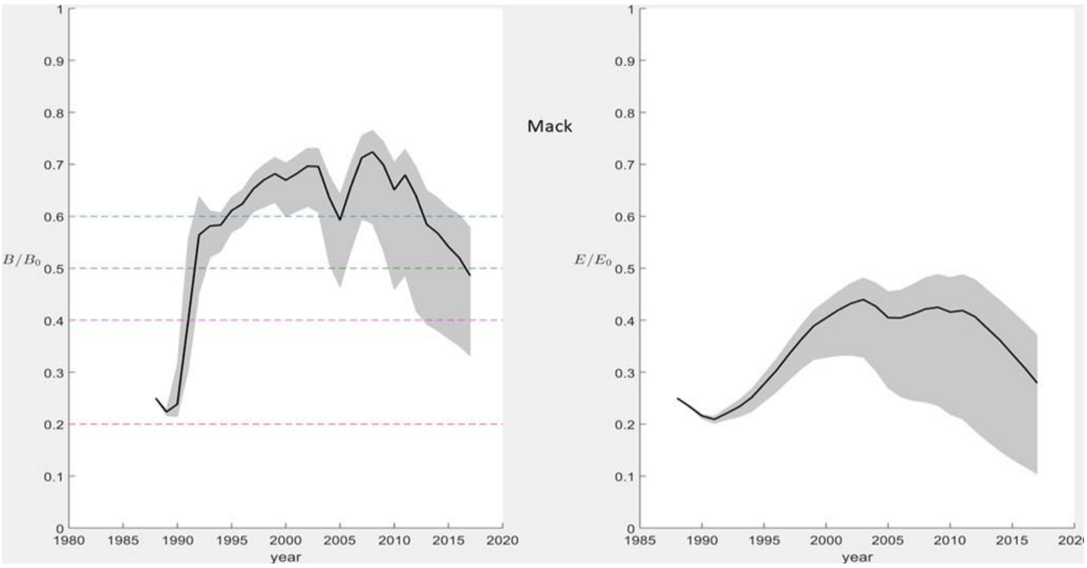
a) Greater depletion rate ($\psi_{low} = 0.15$)



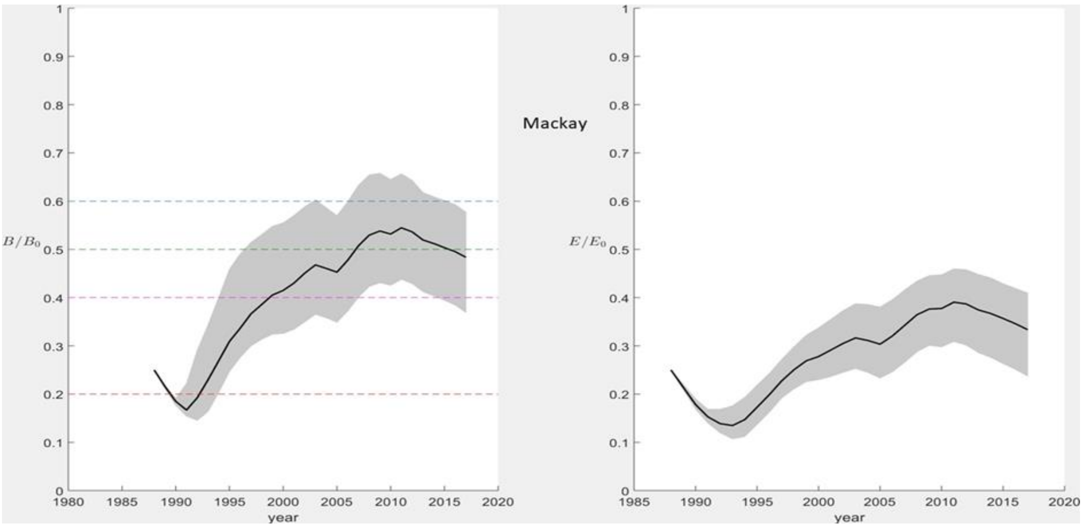
b) Lesser depletion rate ($\psi_{high} = 0.35$)



c) Increasing catchability (q_{inc})



d) Recreational harvest – addition of constant harvest = 21 tonnes



e) Recreational harvest – addition of constant proportion = 37 per cent

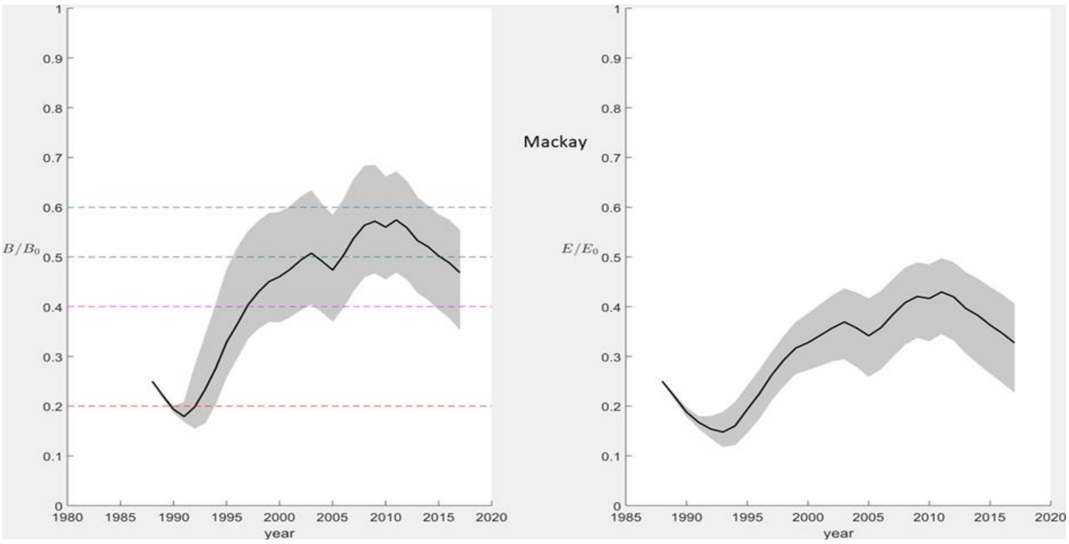


Figure 38: Sensitivity analysis of Mackay barramundi stock status indicators B/B_0 and E/E_0 for (a) greater depletion, (b) lesser depletion, (c) increased catchability, (d) recreational harvest constant tonnage and (e) recreational harvest constant proportion. The blue dashed line is the 60 per cent 2027 target of the SFS, the green dashed line is 50 per cent biomass ratio (MSY), the pink dashed line is the 40 per cent 2020 target of the SFS and red dashed line is the 20 per cent biomass ratio (Commonwealth limit reference point).

4.5. Central East Coast

The Central East Coast (CEC) genetic stock was significantly affected by the contribution of stocked barramundi to the commercial fishery in 2011 (i.e., with the overtopping of Awoonga Dam) and subsequent increases in catch and catch rates (Figure 39,Figure 3).

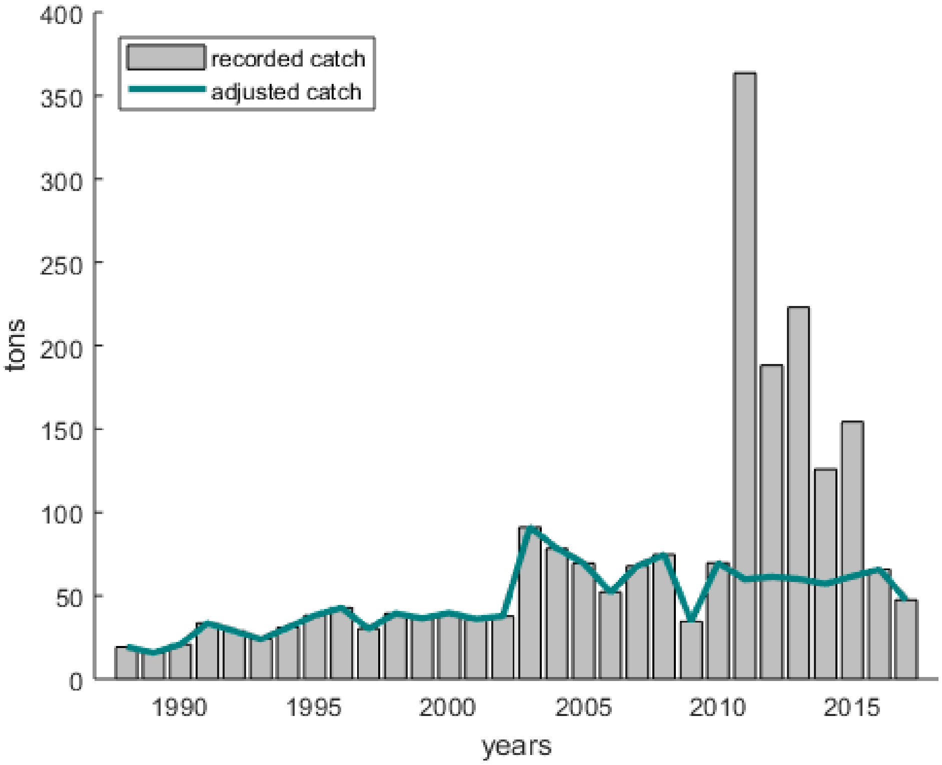


Figure 39: Central East Coast barramundi stock catch by year. Source: CFISH logbook database, Fisheries Queensland. The green line indicates the adjusted catch, which was smoothed across 2011 to 2015 account for the contribution of stocked fish to the commercial catch.

The flooding in late December 2010 and January 2011 caused barramundi, stocked in upstream impoundments (such as Awoonga Dam) and waterways of the CEC stock region, to escape and become available to the commercial fishery. Our attempt to incorporate the number of barramundi fingerlings released within the Central East Coast stock (Appendix B) into the current assessment model did not provide stable results. Instead, we use a smoothing technique to remove the bias in catch and catch rates in the years 2011 to 2015 (as an index of abundance) due to stocked fish. We replaced the catch in each of the years 2011, 2012, 2013, 2014 and 2015 by the moving average of the four preceding years, see the green curve in Figure 39.

The population model was then iterated with the adjusted catch for the years 2011 to 2015 and the model parameters were optimised by fitting to CEC stock standardised catch rate data but only for 1988 to 2010 (i.e., before the dramatic increase in catch associated with the escape of stocked barramundi following flooding).

This technique yielded plausible results and potentially better represents the underlying population dynamics of the CEC barramundi stock. Nonetheless, results should be interpreted with caution. Note that the smoothing technique yields annual catch estimates that do not have to reflect the actual fishing pressure and catch. The model does not assess the effects of the introduction of Capricorn Coast net-free zone at the end of 2015.

4.5.1. Stock status indicator results

The sharp increase in the standardised catch rates after 2010 (Figure 3) allows the exploitable biomass to increase and recover from the assumption of an initial depletion rate in 1988 of 0.25.

The CEC barramundi stock the exploitable biomass ratio B/B_0 was estimated in 2017 to be 0.71 (Table 11), with an egg production ratio estimated at 0.5. These values assumed that the annual catch derived from the smoothing technique is representative for the actual catch of the wild population. If the catch of the wild population was actually greater, then fishing pressure would have been higher which would have caused at least a slowing in the recovery of the wild population’s biomass.

Table 11: Central East Coast barramundi stock median values of stock status indicators for selected years.

CEC	1988	1995	2000	2005	2010	2015	2017
B/B_0	0.25	0.64	0.70	0.66	0.74	0.72	0.71
E/E_0	0.25	0.31	0.44	0.49	0.49	0.50	0.50
B/B_{msy}	0.71	1.04	1.14	1.07	1.19	1.17	1.15
F/F_{msy}	0.37	0.51	0.48	0.89	0.80	0.73	0.57

In Figure 40, there is a steep increase in the exploitable biomass ratio between 1991 and 1996. This rapid increase can be explained by a combination of, at least three, interacting factors. First, the model estimated L_∞ was the largest of all barramundi stocks considered; suggesting the presence of large females contributing to reproduction. Second, compared to the average catch rate during 1988-90, there were significant increases in two subsequent 3-year periods of 42.6 per cent and 46.7 per cent, respectively. Third, the rough 3-year lag before the recovery in recruitment manifests itself in exploitable biomass also contributed to the observed increase.

To elaborate the above in a little more detail note that, for the CEC barramundi stock, the within-model (base case) estimated value of L_∞ was 1549 mm (with k = 0.17, a_0=-0.41). This results in a fairly steep von Bertalanffy growth curve. The consequence of a steep growth curve for barramundi is that certain age-classes are vulnerable to fishing mortality for only a short time. This is due to the dome-shaped selectivity curve and a maximum legal size of 1200 mm. Hence, in the CEC stock older fish are less likely to be caught, thus increasing the egg production of the stock, subsequent recruitment and stock recovery.

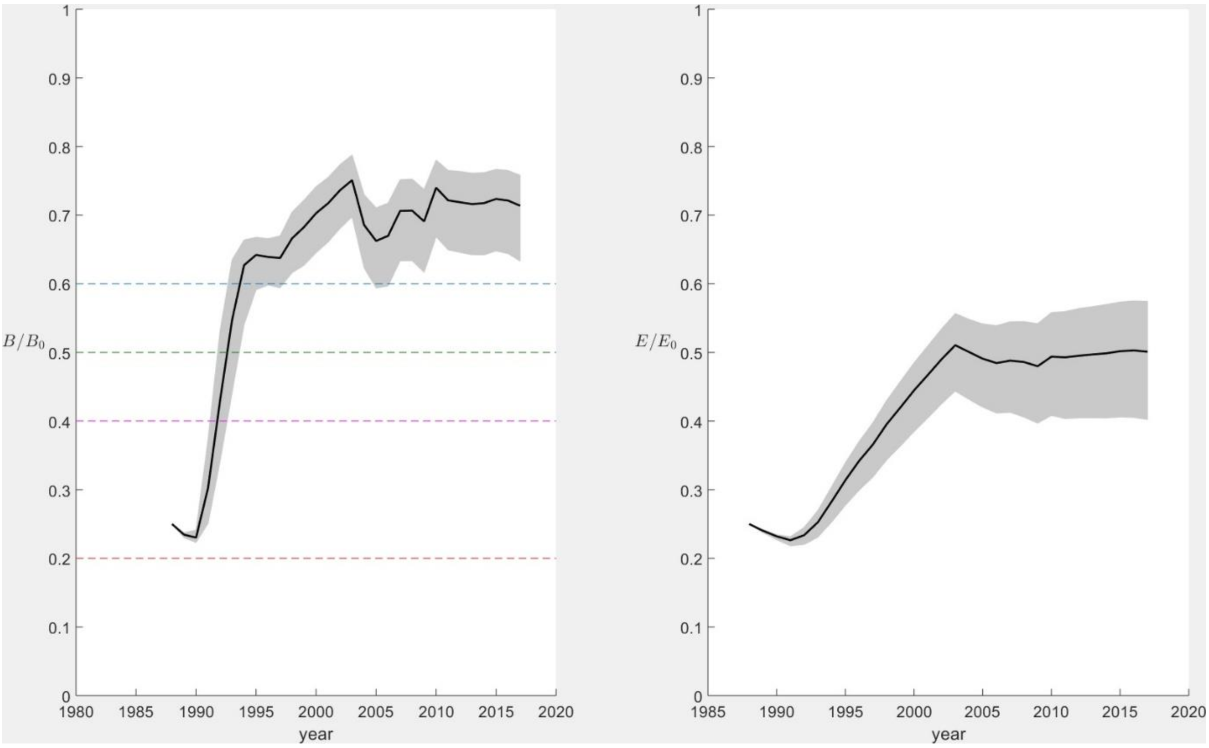


Figure 40: Central East Coast barramundi stock status indicators. The blue dashed line is the 60 per cent 2027 target of the SFS, the green dashed line is the 50 per cent biomass ratio (MSY), the pink dashed line is the 40 per cent 202 target of the SFS and red dashed line is 20 per cent biomass ratio (Commonwealth limit reference point).

4.5.2. Goodness-of-Fit

Goodness-of-fit to the annual standardised catch rate (see Appendix C) is displayed in Figure 41. For the CEC stock, the population model somewhat replicates the patterns in catch rate, but over estimates catch rates between 1997 and 2002.

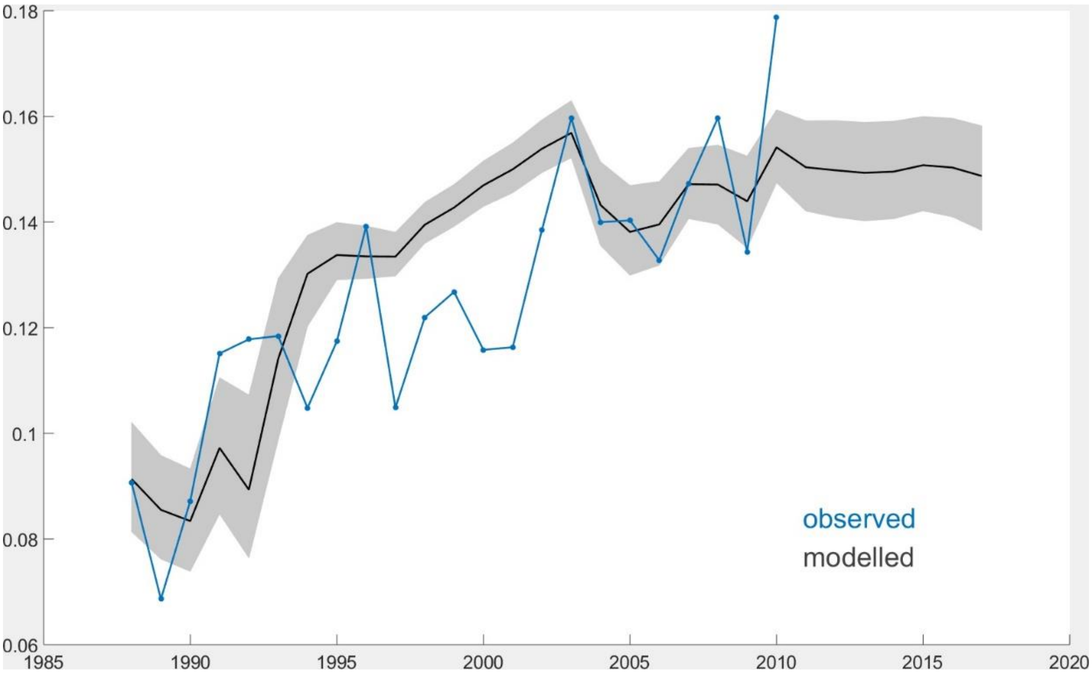


Figure 41: Central East Coast barramundi stock standardised catch rate goodness-of-fit where the observed annual standardised catch rate is the blue line and modelled estimated is the black line

Goodness-of-fit to the Fishery Monitoring age-frequency data for 2007 to 2010 are given in Figure 42 and indicates that the population model replicates some but not all of the patterns in the age-frequency data variation. For further discussion on variation in age-frequency proportions (see Section 4.6).

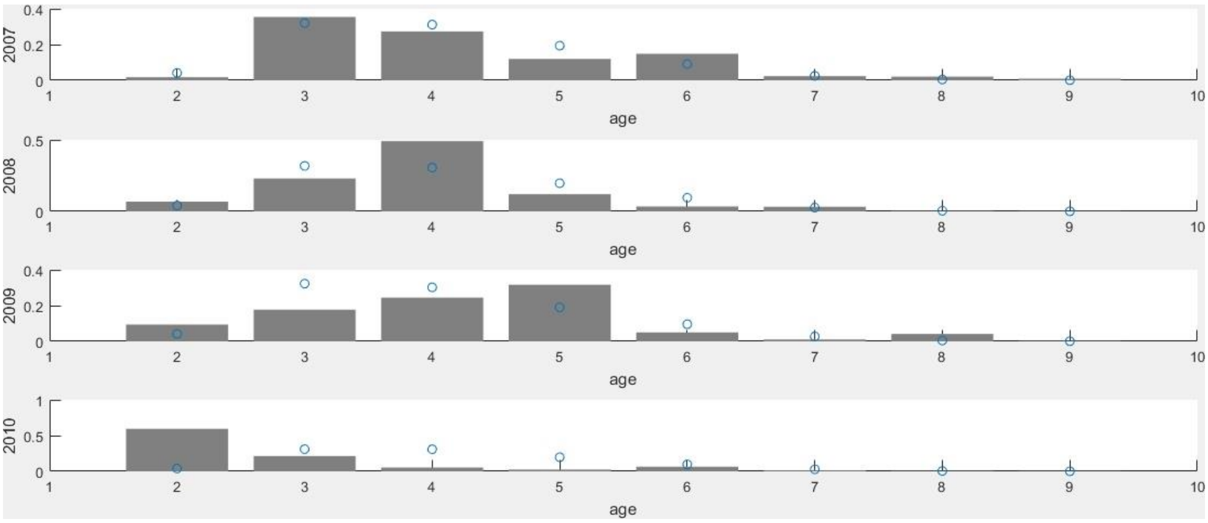


Figure 42: Central East Coast barramundi stock age-frequency goodness-of-fit where observed data are the bars and modelled estimated are the circles. Only age-frequencies for 2007 to 2010 were used in model fitting for this stock.

4.5.3. Total Allowable Catch Scenarios

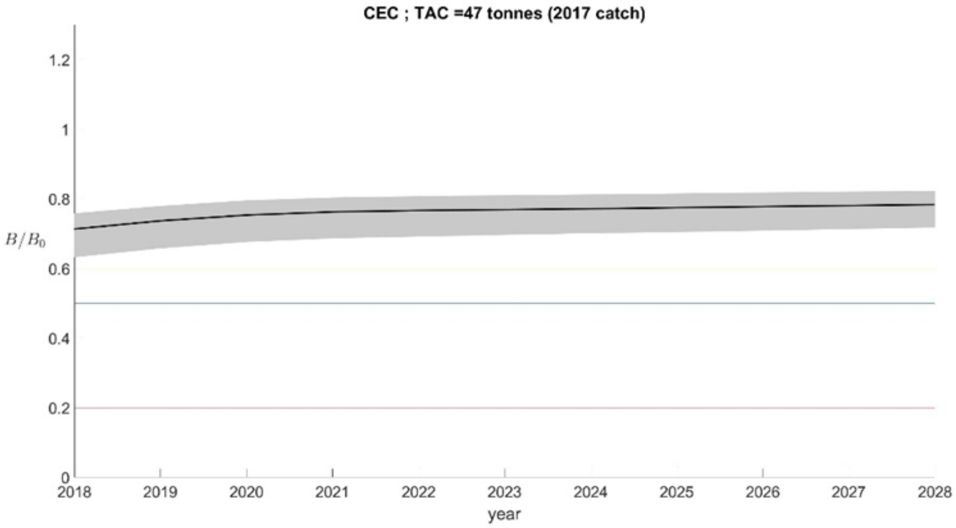
Predicted trends in exploitable biomass under alternate scenarios of constant Total Allowable Commercial Catch (TACC) were investigated.

A constant TACC of 47 tonnes (i.e., the 2017 catch) yields an exploitable biomass ratio B/B_0 of 0.75 by 2027.

A constant TACC of 58 tonnes (average adjusted catch last five years) yields an exploitable biomass ratio of 0.73.

A TACC of 82 tonnes, a relatively high harvest level, still avoids a decline below the exploitable biomass ratio of 0.6 in 2027.

Note that a constant TACC of 91 tonnes forces the exploitable biomass ratio to just below 0.6 in 2027 and indicates continuing decline.



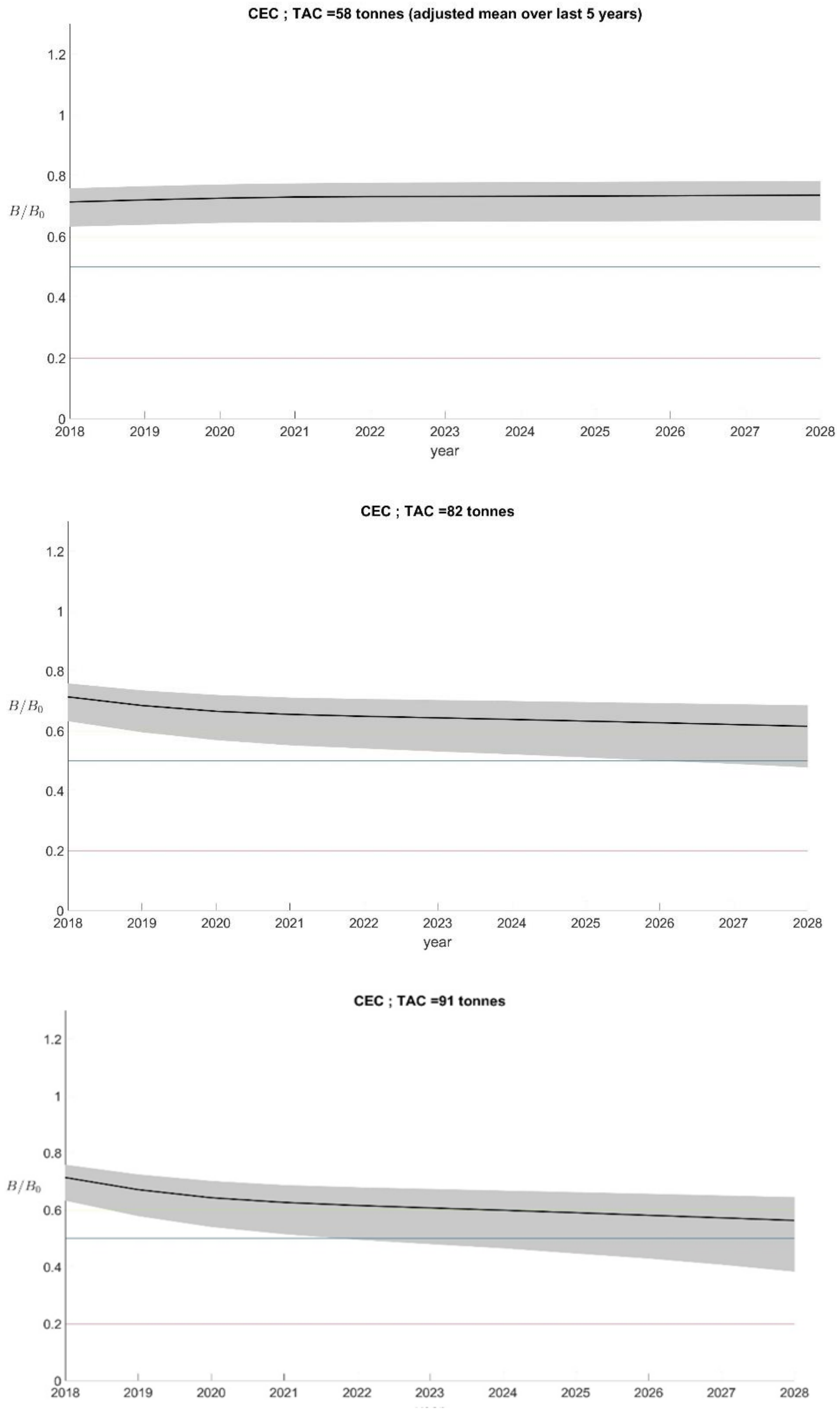


Figure 43: CEC barramundi stock modelled effects of constant Total Allowable Commercial Catches (TACC) for (a) 47 tonnes, (b) 58 tonnes, (c) 82 tonnes and (d) 91 tonnes on the projected exploitable biomass to virgin biomass ratio 2018 to 2028.

4.5.4. Sensitivity Analysis

Three different types of scenarios were investigated for sensitivity to the model assumption. The refitted model parameter estimates, for all scenarios, are presented in Appendix F, Table 20. Stock status indicators are presented in Table 12 and Figure 45.

Since this stock was most affected by flooding events in 2010/2011, the robustness of the scenarios is based on the assumption that the moving average, explained in Section 4.5.1 is a good approximation of wild barramundi population dynamics in the years following flooding (i.e., 2011-2015) in the Central East Coast.

a) Initial depletion rate ($\psi_{low} = 0.15$, $\psi_{high} = 0.35$)

Under the base case initial depletion rate $\psi = 0.25$, the CEC barramundi stock exploitable biomass ratio B/B_0 was estimated in 2017 to be 0.71.

If a greater depletion rate ($\psi_{low} = 0.15$) was assumed, the exploitable biomass ratio was estimated in 2017 to be 0.62. The egg production ratio was estimated in 2017 at 0.37 for $\psi_{low} = 0.15$, compared to its base case value of 0.5. If the depletion rate was lesser, that is $\psi_{high} = 0.35$, the exploitable biomass ratio was estimated in 2017 to be 0.74 and the egg production ratio was estimated to be 0.57.

b) Increase in catchability (q_{inc})

For the CEC stock, q_{inc} was estimated to be 0.447, corresponding to a catchability in 2017 of 1.5 times the average catchability from 1988-1992. If catchability had increased in the CEC stock, the estimated biomass ratio B/B_0 in 2017 was 0.63, compared to 0.71 for the base case. The egg production ratio E/E_0 was estimated to be 0.37 in 2017, compared to 0.50 in the base case.

c) Recreational harvest

For the CEC, the scenario of a constant recreational harvest of 12 tonnes resulted in a similar total harvest (observed commercial and estimated recreational) as the scenario of a constant per cent recreational harvest of 24 per cent of the commercial harvest (Figure 44; Figure 45). Hence, the estimated biomass ratio and egg production ratio were similar in both cases. Under either recreational harvest scenario, the exploitable biomass ratio B/B_0 was estimated in 2017 lower than the base case with value of 0.66 compared to 0.71 for the base case. The egg production ratio E/E_0 was similarly affected, estimated in 2017 to be 0.44 compared to 0.50 for the base case (Table 12).

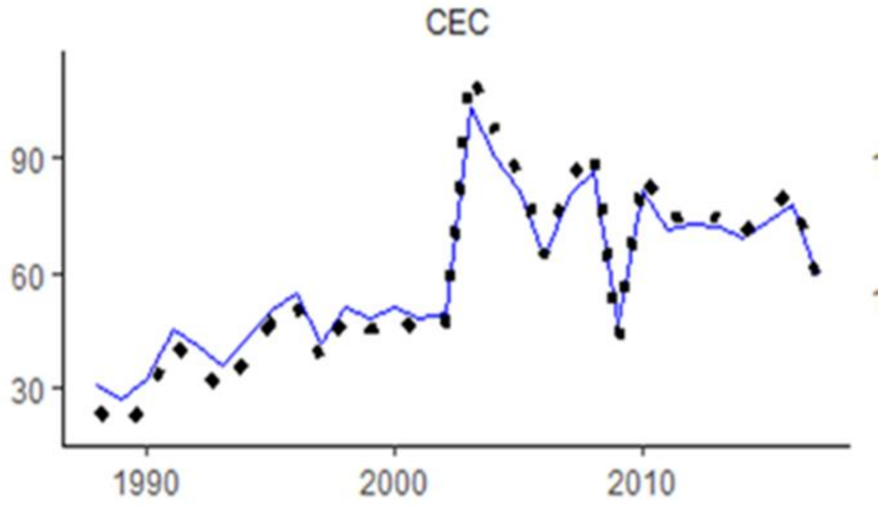
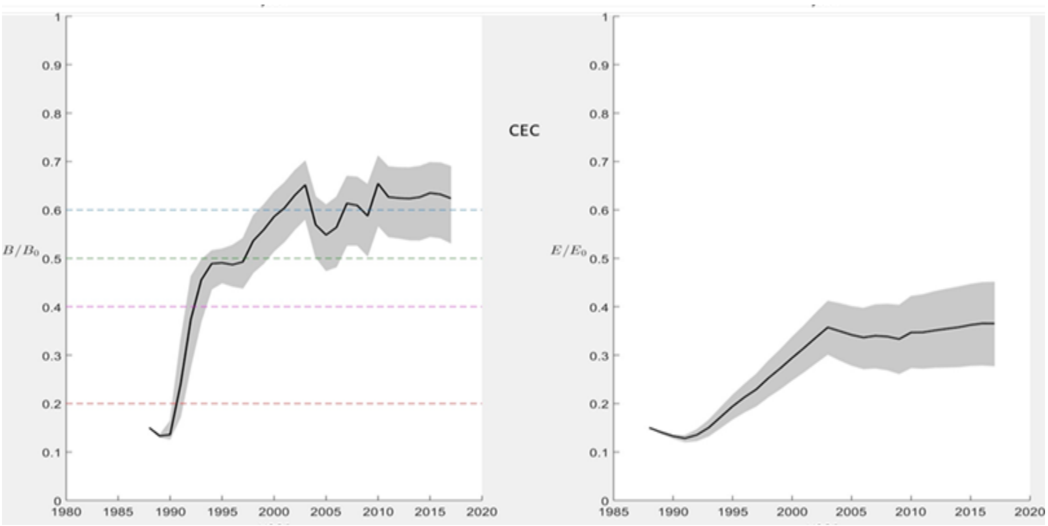


Figure 44: Central East Coast barramundi stock total harvest estimates (commercial and recreational combined). The solid blue line assumes a total harvest (commercial + 12 tonne recreational), the dotted black line a proportional harvest (commercial + 24 per cent of commercial for recreational).

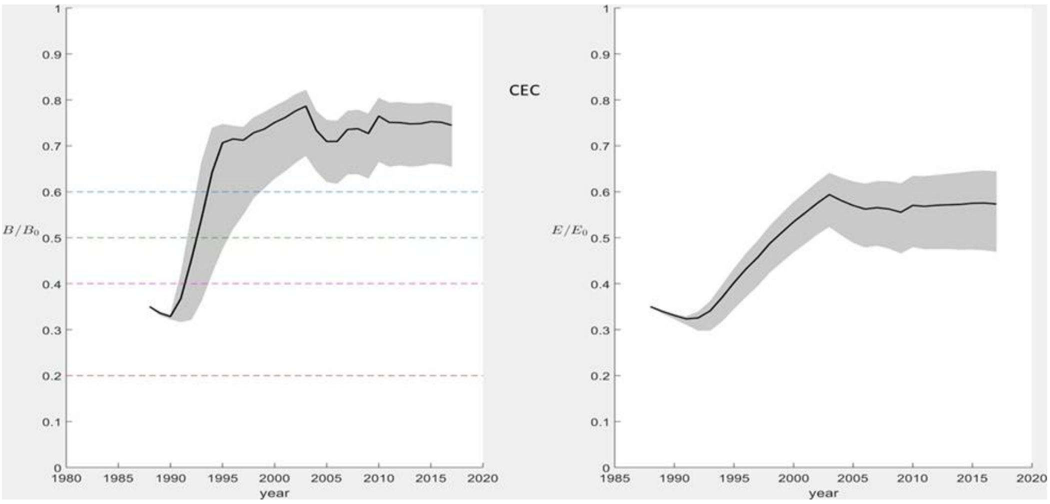
Table 12: Central East Coast barramundi stock median values of stock status indicators (exploitable biomass to virgin biomass and egg production ratio) estimated under alternate model scenarios for selected years.

CEC	1988	2005	2008	2012	2015	2017
Base case						
B/B_0	0.25	0.66	0.71	0.72	0.72	0.71
E/E_0	0.25	0.49	0.49	0.50	0.50	0.50
Sensitivity results						
$B/B_0\ \psi_{\text{low}}$	0.15	0.55	0.61	0.62	0.63	0.62
$E/E_0\ \psi_{\text{low}}$	0.15	0.34	0.34	0.35	0.36	0.37
$B/B_0\ \psi_{\text{high}}$	0.35	0.71	0.74	0.75	0.75	0.74
$E/E_0\ \psi_{\text{high}}$	0.35	0.57	0.56	0.57	0.58	0.57
$B/B_0\ q_{inc}$	0.25	0.61	0.66	0.66	0.65	0.63
$E/E_0\ q_{inc}$	0.25	0.44	0.41	0.39	0.38	0.37
B/B_0+ Rec con	0.25	0.61	0.65	0.66	0.67	0.66
E/E_0+ Rec con	0.25	0.42	0.42	0.43	0.44	0.44
B/B_0+ Rec prop	0.25	0.62	0.65	0.66	0.67	0.66
E/E_0+ Rec prop	0.25	0.45	0.43	0.44	0.44	0.44

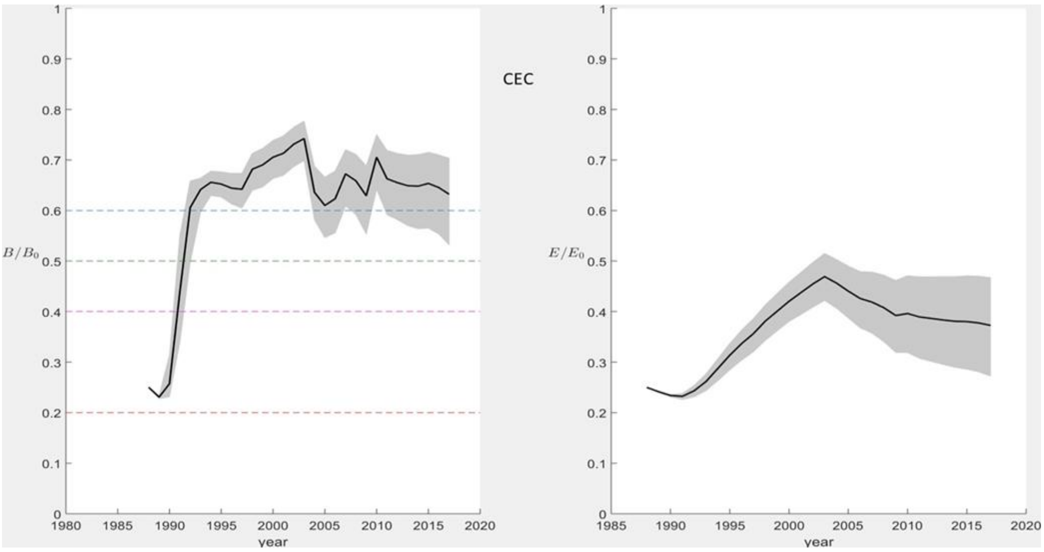
a) Greater depletion rate ($\psi_{low} = 0.15$)



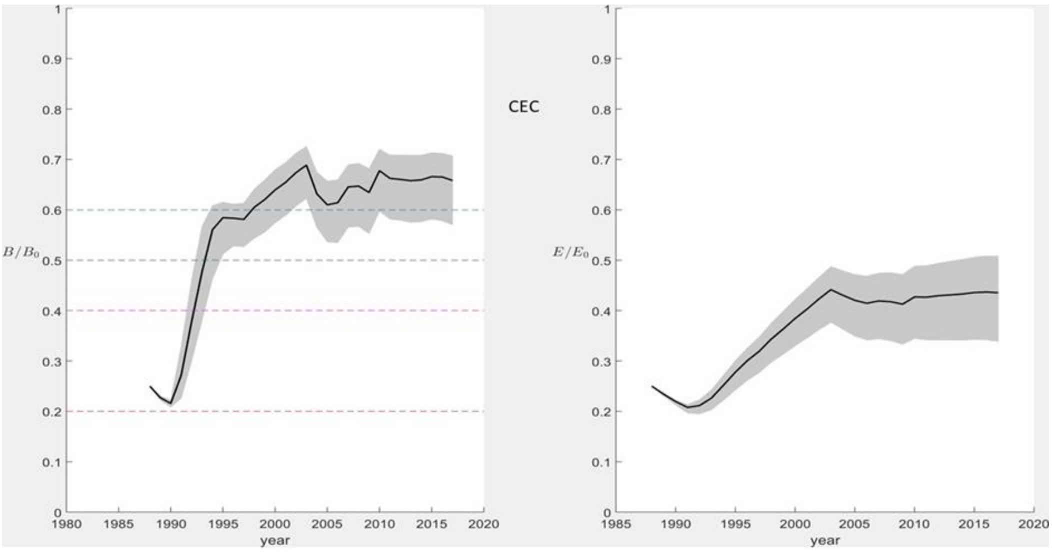
b) Lesser depletion rate ($\psi_{high} = 0.35$)



c) Increasing catchability (q_{inc})



d) Recreational harvest – addition of constant harvest = 12 tonnes



e) Recreational harvest – addition of constant proportion = 24 per cent

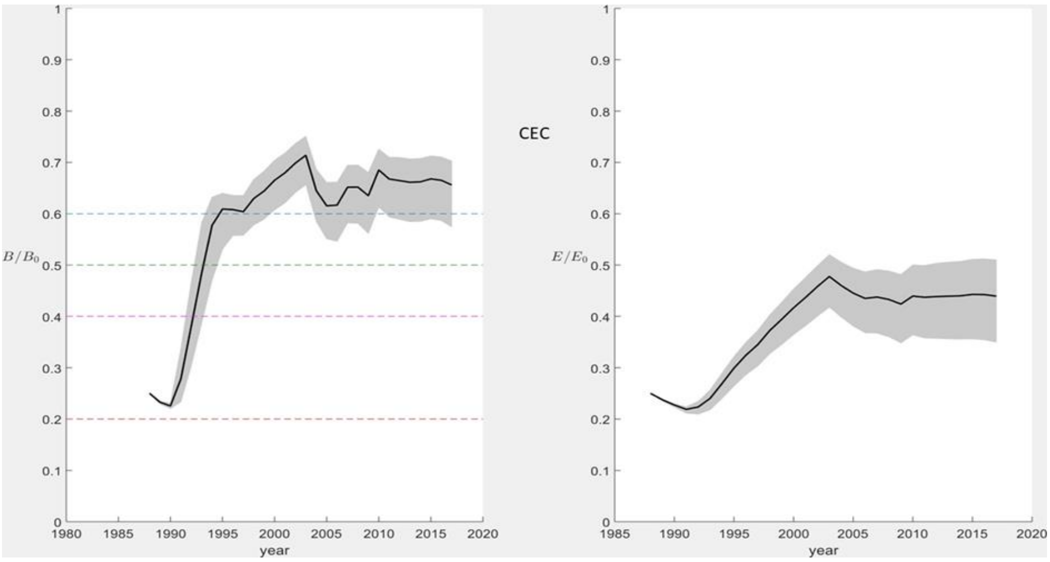


Figure 45: Sensitivity analysis of Central East Coast barramundi stock status indicators B/B_0 and E/E_0 for (a) greater depletion, (b) lesser depletion, (c) increased catchability, (d) constant recreational harvest, and (e) recreational harvest constant proportion. The blue dashed line is the 60 per cent 2027 target of the SFS, the green dashed line is the 50 per cent biomass ratio (MSY), the pink dashed line is the 40 per cent 202 target of the SFS and red dashed line is 20 per cent biomass ratio (Commonwealth limit reference point)

5. Discussion

Overall, the results from the current assessment indicate the rebuilding barramundi populations in Queensland since the early 1990's. In particular, the main results include:

- Since 1992, there has been a general recovery of barramundi stocks relative to 1988/1989 levels.
- All stocks were estimated in 2017 to be very close to or above 40 per cent exploitable biomass (relative to virgin biomass).
- Recovery was greatest in the Northern Gulf and Central East Coast stock regions.
- Trends in egg production ratios were more variable and less positive than those of exploitable biomass ratios. In particular, in two stocks, egg production ratios have not increased (North East Coast) or only increased moderately (Southern Gulf) relative to 1988/1989 assumed depletion rates.
- Despite the overall recovery in exploitable biomass, each stock contains periods of stability and oscillations that are probably related to environmental factors, such as floods or droughts.
- The trends of recovery, stability or oscillation are generally robust, being persistent across various the scenarios tests of model sensitivity to initial depletion rate, increasing catchability and the incorporation of recreational harvest.
- Results were also consistent with trends obtained from simpler surplus models and other stock assessments.
- Model results are sensitive to the initial depletion rates. If depletion were greater than that assumed for the base case, the exploitable biomass and egg production ratios would be smaller. Alternatively, if the depletion were lesser than assumed for the base case, exploitable biomass and egg production ratios would be greater.

We caution against overly optimistic interpretation of the current results in part because of the slow recovery indicated by the egg production as well as the model limitations. The slow recovery of barramundi populations, in terms of egg production, is likely to be a true finding, despite the inherent limitations faced in modelling this species. Barramundi are protandrous hermaphrodites, maturing as males at two to five years and then changing sex to become females at five to seven years (Davis 1985). Thus, it takes time (approximately six years) for generational rebuilding.

Given the conceptual misinterpretation of maximum sustainable yield for species with model parameters varying in time due to environmental or genetic changes, we have focused on ratio stock status indicators with respect to the virgin year; that is exploitable biomass ratio B/B_0 and egg production ratio E/E_0. Trends in these ratios provide relevant information to support sustainable fisheries management. For instance, an extended period of sustained recovery of a stock status indicator such as the ratio of exploitable biomass to virgin biomass, indicates that the risk of over fishing is receding, assuming model conditions are accurate.

However, it is essential to point out several limitations of the underlying analyses that must be remembered when drawing conclusions from the current results. As with most quantitative scientific models of man-nature impacted phenomena, the outputs are heavily influenced by at least the following underlying factors:

1. The accuracy, completeness and relevance of data used to calibrate the scientific model.
2. The validity of assumptions concerning the initial conditions and underlying model structure, including key life history parameters.
3. The inclusion of key external variables affecting the population dynamics.

Below, we briefly elaborate on each of these factors.

1. **Accuracy of data used to calibrate the model**

In the current assessment, it was assumed that CFISH data were acceptably accurate and that the standardised catch rate derived from the CFISH data provided an accurate measure the of abundance of legal-sized barramundi in each stock in each year. This assumption is imperfect as the standardisation cannot account for, amongst other factors, all of the many and varied management interventions, nor undocumented changes in gear technology, nor changes due to socio-economic drivers of fisher behaviour.

2. **Validity of assumption of initial conditions and model structure**

Similarly, our assumptions concerning initial conditions in 1989 (or 1988) assumed that barramundi were overfished at that time with about 20 per cent virgin biomass in the Gulf and 25 per cent virgin biomass in the east coast as per Campbell (2008) and Gribble (2004). However, it is only an assumption in view of the fact that the virgin biomass of barramundi is not known. An attempt has been made to address this assumption by considering different depletion ratios.

Furthermore, while our technical assumptions are widely accepted in the fishery modelling literature and practice, it is always important to recognize the possibility that some of them may be violated for a particular species in a particular region. For instance, the increase in key stock status indicators are based on the assumption that increased catch rate over time reflects increased biomass. This implicitly assumes catchability does not vary significantly during the same period. Although this is a common assumption in stock assessment modelling, there is evidence of an increased intensity of the fishing effort and environmental conditions. Factors such as droughts or flooding or the associated overflowing of stocked dams will have a direct impact on the movement of the species, and therefore the fishers are more or less likely to catch fish. An increasing catchability and the implications on the modelled stock abundance were addressed.

3. **Inclusion of key external variables**

Environmental factors such as rainfall and associated flooding and droughts have an important impact on the dynamics of barramundi populations (e.g., Staunton-Smith *et al*., 2004; Robins *et al*., 2005). This is supported both by earlier studies by Tanimoto *et al*. (2012) and our own preliminary calculations. Indeed, a conceptual model incorporating river flows had been developed as part of this study. The time scope of the current assessment did not offer an opportunity for a detailed calibration and evaluation of this model and the associated river flow data.

Key Recommendations

- Continue sampling length, age and gender information for barramundi in sufficient detail to capture the spatial and temporal variability within Queensland stocks.
- Given the results for the Mackay stock, consider sampling age and length of the commercial harvest, in that region.
- Validate commercial catch and effort data.
- Determine the impact of barramundi stocked into impoundments and waterways on the wild-capture fishery in each stock, as stocked fish inject uncertainty into quantitative assessment. All stocking events should be quantitatively recorded by Fisheries Queensland in a central

database including at a minimum: date, number of fish stocked, average length, and location of release.

- Despite being relatively well studied, there remain key gaps in the life history information of barramundi in northern Australia that are critical to quantitative population modelling. In particular stock specific abundance and persistence of large barramundi (≥1000 mm), upon which L_∞ is estimated is uncertain. This is critical to the estimation of growth curves which in turn affects egg production.
- The inclusion of environmental drivers such as river flow in stock assessments should continue to be a goal for barramundi, with ongoing research and data collection to support this.
- It is likely that the abundance of barramundi year-classes changes in response to the environmental dynamics of floods and droughts experienced in each stock region. Regional management procedures need to be precautionary and adaptable in this regard. Policies in regards to Total Allowable Catch should be reviewed at least every two years (if not annually) per stock region, to synchronize recommended biological harvest with cycles in the barramundi abundance driven by strong and weak recruitment events in barramundi populations.

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7. Appendices

Appendix A - Compilation of management arrangements for Queensland barramundi

Year	Management Measure	Instrument	Source
Unknown	Minimum mesh size 11.5 cm for set-nets inside rivers on the Qld east coast (QEC)		
Unknown	Weekend closure in most rivers and creeks on the (QEC)		Russell (1988)
Unknown	All freshwaters closed to commercial fishing		Russell (1988)
Unknown	Total fishing closure immediately upstream and downstream of coastal fish ladders		
1877	Minimum legal size 16 oz (weight)	***The Qld Fisheries Act of 1877***	Haysom (2001)
1914	Minimum legal size 14" (=35.5 cm)	***The Fish and Oyster Act of 1914 (amended in 1918, 1932, 1935, 1945, 1955)***	Glaister (1990)
1932	Minimum legal size increased to 15" (=38.1 cm)		Glaister (1990)
1955	Minimum legal size increased to 20" (=50.8 cm)		Glaister (1990); QDHM (1959)
1957		***The Fisheries Act of 1957 (amended in 1959, 1962, 1974)***	Haysom (2001)
1976		***The Queensland Fisheries Act of 1976 (amended in 1981, 1982)***	Haysom (2001)
1977	Partial closure of 16 GoC rivers and six QEC rivers to commercial net fishing		QFMA (1990); Elmer (1987)
1981	Closed fishing (and take) season 1 November to 1 February (GoC & QEC)	***Barramundi management strategies implemented***	Garrett & Russell (1982)
	Separate limited entry licences (endorsements) for commercial fisheries in the GoC & QEC		Garrett & Russell (1982)
	Minimum mesh size for all set gill nets increased to 150 mm GoC		Garrett & Russell (1982)
	Recreational possession limit of five fish per person QEC		Garrett & Russell (1982)

Year	Management Measure	Instrument	Source
	Protection of barramundi nursery habitats through legislated habitat reserves, fish sanctuaries and fish refuge areas		Garrett & Russell (1982)
	Standardised set-net mesh size at 150 mm (6") north of Cape Flattery on QEC and in the GoC		QFMA (1987)
	Monthly logbook (production return) GOC commercial fishery		
1982	Management Plan for barramundi: restrictions on nets and gears used by commercial fishers; restrictions on how commercial set-nets may be used in rivers and foreshores; reviews of fish habitat areas; limits on size and numbers of commercial vessels used in the fishery	***Queensland Fishing Industry Organisation and Marketing Act 1982***	QFMA (1987)
1988	GOC licence moved from being issued to individuals to being attached to vessels		Ward (2003)
	Introduction of a compulsory daily logbook		
1989	Minimum legal size increased to 55 cm		Russell & Hales (1993)
	Minimum mesh size for set-nets in rivers and creeks increased to 150 mm		DPI (1989)
	Maximum mesh size for set-nets of 245 mm (Max fish size approx. = 1200 mm due to selectivity)		DPI (1989)
	Closures to commercial net fishing: Johnstone River; Plantation Creek; remainder of Burdekin River (delta); remainder of Haughton River; remainder of Proserpine River; Water Park Creek above Kelly's landing; Cawarral Creek; Calliope River upstream of Devil's Elbow		QFMA (1990)
	Closure to commercial net fishing except bait and general purpose nets: remainder of the Pioneer River		QFMA (1990)

Year	Management Measure	Instrument	Source
	Closures to all net fishing and the taking of barramundi: Russell/Mulgrave Rivers		QFMA (1990)
	Removal of existing net fishing closures: Barratta Creek; O'Connell River (bait and general purpose nets only)		QFMA (1990)
1990	Prohibition of sale of barramundi under section 35 of the *Fishing Industry Organization & Marketing Act* (i.e., sale of recreationally taken fish in excess to the requirements of the recreational fisher)		QFMA (1990)
1992	Maximum legal size set at 120 cm	***East Coast barramundi Set (Gill) Net Fishery Management Plan***	QFMA (1990)
	Minimum legal size increased to 58 cm (QEC)		Russell & Hales (1993)
	Introduction of 1 km spawning zones around the mouths of creeks and rivers during the closed season QEC		Cairns Post (1992)
1994		***Queensland Fisheries Act 1994***	
1995		***Queensland Fisheries Regulations 1995***	
1996	Minimum set-net mesh sizes (GoC) increased to 162.5 mm (but not more than 245 mm)	***Fisheries (Gulf of Carpentaria Inshore Fin Fish) Management Plan***	Garrett (1997)
	GoC seasonal closure for all inshore net fishing changed from a fixed Nov-Jan inclusive to a variable closure between Oct-Jan inclusive to include the max number of spring and summer full and new moons and night time high tides		Roelofs *et al*. (2003)
1997	Dugong Protection Areas[A] introduced QEC = spatial closures to net fishing		Williams (2002)
	Spatial closures and gear restrictions around the Sweers Island GoC as part of the Gulf Management Plan for dugong protection.		

Year	Management Measure	Instrument	Source
1999	Separation of the GoC licences to symbols within the GOCIFFF to N3 (<7 nm from coastline –Inshore Gillnet Fishery) and N9 (7 to 25 nm from coastline – Offshore Gillnet Fishery)	***Fisheries (Gulf of Carpentaria Inshore Fin Fish) Management Plan 1999***	
	Minimum legal size increased to 60 cm (GoC)		
	Net attendance requirements legislated		
2008	Revised management arrangements	***Fisheries Regulation 2008***	
2011	Revised management arrangements	***Fisheries (Gulf of Carpentaria Inshore Fin Fish) Management Plan 1999*** repealed**,** now regulated via ***Fisheries Regulation 2008***	
2012	Minimum legal size decreased to 58 cm (GoC)		Tanimoto *et al*. (2009)
	GoC spawning closure start dates 7 October to 1 February		
2015	Freshwater closures for weirs standardised		
	Net Free Zones introduced November 2015 for Cairns, Mackay and Fitzroy areas, becoming effective in February 2016		

[A] Dugong Protection Areas: Hinchinbrook and Taylor Beach; Cleveland Bay and Bowling Green Bay; Upstart Bay; Edgecumbe Bay; Repulse Bay, Newry Region and Sandy Bay; Ince Bay. Llewewellyn Bay, and Claireview Region; Shoalwater Bay and Port Clinton; Rodds Bay

Appendix B - Collated information on stocked barramundi for each genetic stock in Queensland

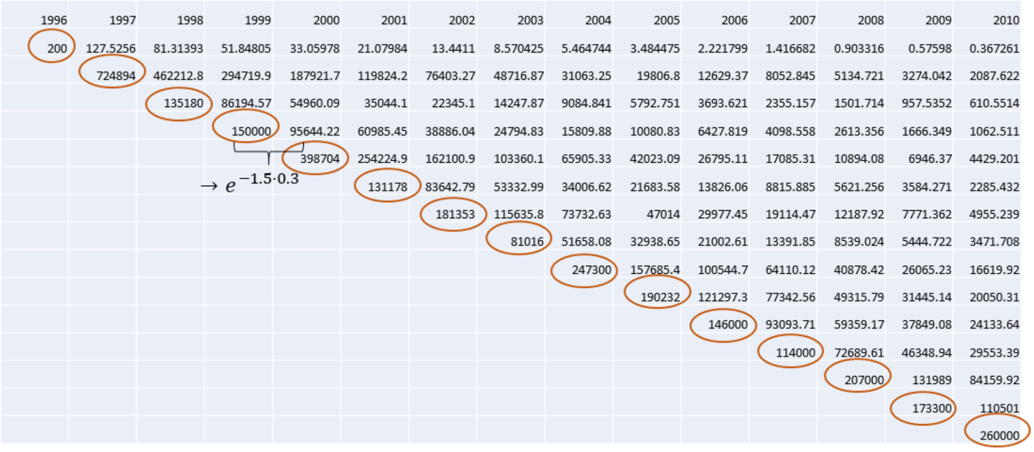
Information in the table below is a summary of data collated from: Fisheries Queensland stocking databases (general, SIPS, RFEP and impoundment stocking history) and records compiled by regional fisheries officers (i.e., P. Long, S. Pobar, and M. Pearce). This information (e.g., date, location, number stocked, TL, supplying hatchery and stocking group) was supplemented and corroborated (where possible) between data sources as well as against information available on the internet, newspaper stories and stocking group databases. The numbers in Table 13 represent the total number of barramundi fingerlings/juveniles released within the spatial extent of a stock (or sub-stock) minus the number of fingerlings/juveniles stocked into impoundments where: (i) fish were unlikely to survive overtopping events and move to downstream reaches, as well as (ii) fish that were likely to have died as a consequence of documented fish kills or large scale cold snap events. 'Year-class stocked' represents the nominal birth date (i.e., 1 January) of released fish.

Table 13: Numbers of barramundi fingerlings stocked within genetic stock regions that potentially contributed to the estuarine population, see Campbell et al. (2017).

	SGoC	NEC		CEC		Mackay
Year Class stocked	SE sub-stock (16ºS to NT border)	Dry Tropics (19ºS to 20ºS)	Wet Tropics (15ºS to 19ºS)	Fitzroy	Gladstone	
1986			13,787			
1987						
1988		87,000				
1989		400	10,000			
1990			29,500	1,132		
1991		126,000	21,360			
1992		235,000	2,400	50,000		
1993		98,878	20,398	50,000		
1994		66,650	101,314	40,000		
1995	50,000	62,000	100,206	39,500	200	
1996	292,000	40,463	62,600	36,400	724,894	
1997		161,500	69,743	56,000	135,180	
1998	500	165,020	114,193	8,000	152,450	
1999	70,000	114,246	79,735	86,938	404,704	
2000		60,500	64,393	34,725	131,178	65,000
2001		94,010	53,990	35,600	185,353	157,000
2002		119,976	38,053	20,200	85,716	32,760
2003	12,500	248,275	85,201	62,700	248,362	75,300
2004	25,926	336,000	84,050	44,000	193,396	20,180
2005		68,000	30,397	28,800	149,200	33,688
2006	25,000	115,200	750		117,700	27,033
2007	10,700	109,801	7,000	52,726	207,000	71,005
2008	4,600	58,890	4,245	89,300	176,300	50,334
2009	10,000	58,995		58,092	260,000	24,108
2010	12,000	110,250	20,164	72,375	207,000	37,981
2011	232	17,318		88,730	347,000	40,973
2012	3,232	55,893	2,000	64,400	223,500	15,259
2013	41,000	17,700		16,100	211,075	22,651
2014						1,000
Total	**557,690**	**2,679,434**	**1,025,619**	**1,653,815**	**4,160,208**	**674,272**

Based on Table 13, we considered the Gladstone region as this was heavily flooded in 2010/2011 and led to a significant increase in total catch in the Central East Coast stock. The most right column indicates the number of fish that, disregarding fishing mortality, could have survived up to the end of 2010.

Table 14: Estimated number of stocked barramundi per age that could have influenced the CEC catch in 2011.



1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
200	127.5256	81.31393	51.84805	33.05978	21.07984	13.4411	8.570425	5.464744	3.484475	2.221799	1.416682	0.903316	0.57598	0.367261
	724894	462212.8	294719.9	187921.7	119824.2	76403.27	48716.87	31063.25	19806.8	12629.37	8052.845	5134.721	3274.042	2087.622
		135180	86194.57	54960.09	35044.1	22345.1	14247.87	9084.841	5792.751	3693.621	2355.157	1501.714	957.5352	610.5514
			150000	95644.22	60985.45	38886.04	24794.83	15809.88	10080.83	6427.819	4098.558	2613.356	1666.349	1062.511
				398704	254224.9	162100.9	103360.1	65905.33	42023.09	26795.11	17085.31	10894.08	6946.37	4429.201
			$\rightarrow e^{-1.5\cdot 0.3}$		131178	83642.79	53332.99	34006.62	21683.58	13826.06	8815.885	5621.256	3584.271	2285.432
						181353	115635.8	73732.63	47014	29977.45	19114.47	12187.92	7771.362	4955.239
							81016	51658.08	32938.65	21002.61	13391.85	8539.024	5444.722	3471.708
								247300	157685.4	100544.7	64110.12	40878.42	26065.23	16619.92
									190232	121297.3	77342.56	49315.79	31445.14	20050.31
										146000	93093.71	59359.17	37849.08	24133.64
											114000	72689.61	46348.94	29553.39
												207000	131989	84159.92
													173300	110501
														260000

In the calibration for the Central East Coast barramundi stock, the number of stocked barramundi was incorporated based on Table 14. Based on conversations with recreational fishers releasing juvenile barramundi into the rivers in CEC, the model was adjusted based on the following assumptions:

- Stocked barramundi had an instantaneous natural mortality rate (M) that is 0.45 compared to modelled wild barramundi that converged to 0.28. This assumption accounted for the likely higher natural mortality for stocked barramundi into account.
- The probability of stocked fish reaching the estuary in 2011 is linearly increasing with their age. The precise percentage was estimated inside the model.
- It was assumed that stocked barramundi did not contribute to reproduction. This accounts for a significant reduction in the reproduction of stocked fish due to the stress of a new habitat.
- Stocked barramundi, on average, had the same growth rate as wild barramundi.

However, model calibration when stocked barramundi were included for the CEC stock led to inconclusive results and an alternative method has been established based on a smoothing technique of the annual catch. The latter was reported in Section 4.5

Appendix C - Standardisation of commercial catch and effort data

The standardisation was based on the CFISH logbook data reported for barramundi commercially caught by gillnets. Further, only entries with a one-day fishing trip (=effort) and reported net-length were considered. Collectively, 92 per cent of the original CFISH logbook data satisfied these conditions and were used in the standardisation. For individual stocks, 91 per cent in the Southern Gulf data satisfied all conditions, 98 per cent of the Northern Gulf, 94 per cent in North East Coast, 90 per cent in Mackay stock and 94 per cent in Central East Coast.

The annual catch in each stock region per Authority Chain Number ($\mathrm{ACN} \cong$ licence) fishing was assumed to follow a multiplicative relationship with respect to fishing days and season. The annual catch depends not only on the fisher (assumed to be identified by the ACN) but also on the fishing season, the net-length and the number of fishing days in that year. For each stock, the monthly catch in year y, in grid-region r, for the ACN using a net-length classified in four levels was therefore assumed to be of the form

$$C_{y,r,\mathrm{net},\mathrm{ACN}} \sim E^{a_1} s_1^{a_2} s_2^{a_3} s_3^{a_4} s_4^{a_5} B_{y,r}, \qquad (1)$$

where E is the number of fishing days in that month of year y, in grid-region r, recorded by ACN using an average of net-length classification, denoted by net. Here, $B_{y,r}$ represents the biomass in year y and region r. Finally, the symbol ~ in the above formula indicates that such annual catch is assumed to be proportional to the product of the factors on the right hand side. Four different ranges of net length were used to classify net-length categories. The range of net length considered for each stock were: Range 1: less than 180m, Range 2: between 180m and 260m, Range 3: between 260m and 400m and Range 4: above 400m. This reduced the impact of net length outliers that were likely caused by inaccurate reporting or data entry errors. The seasonal/tide variables $s_i \in [0,1],\ i = 1, 2, 3, 4$, measured changes in catchability. The parameters a_1, a_2, a_3, a_4, a_5, fitted to the recorded catch data, determine the relative importance of each factor.

For each stock: Southern Gulf (SGulf), Northern Gulf (NGulf), North East Coast (NEC), Mackay and Central East Coast (CEC), a separate analysis was performed, using the same equation to standardise catch.

Log-transforming the multiplicative relationship (1) between catch and effort allowed the analysis using a log-linear model. The analysis was performed in the statistical package R (version: R-3.4.3) using the linear mixed model function lmer from R's lme4-package. The R equation generating the log-linear model for each stock was:

$$\log(\mathrm{C[kg]}) \sim f_y + \log(E[\mathrm{days}]) + \sum_{i=1}^{4} \hat{s}_i + f_{\mathrm{net}} + f_{\mathrm{LAT}} + r_{\mathrm{Grid}} + r_{\mathrm{ACN}} + f_{\frac{\mathrm{wet}}{\mathrm{dry}}}, \qquad (2)$$

where:

- $\log(C[\mathrm{kg}])$: log of monthly catch in year y by ACN in each 30-minute grid.
- f_y: effect of year (abundance index), as a 30-level factor covering the years 1988 to 2017 for stock regions NEC, Mackay, and CEC. Due to outliers in SGulf and NGulf, the standardisation covers the years 1898 to 2017 here in 1989.
- $\log(E[\mathrm{days}])$: converts number of monthly fishing days into log-number of monthly fishing days.
- $\sum_{i=1}^{4} \hat{s}_i$: seasonal effect (Marriott *et al*., 2013), where $\hat{s}_i = \mathrm{mean}(s_i)$. Since the logbook entries are daily entries, but we consider monthly biomass, the mean is taken over all entries in each month.

$$s_1 = \sin\left(2\pi \frac{D}{D_Y}\right), s_2 = \cos\left(2\pi \frac{D}{D_Y}\right), s_3 = \sin\left(4\pi \frac{D}{D_Y}\right), s_4 = \cos\left(4\pi \frac{D}{D_Y}\right),$$

where D is the number of days passed in that year until that fishing trip and D_Y is the total number of days in that year (365; leap year: 366). The mean is taken over the fishing entries in each month.

• f_{net}: net length effect as four level factor dependent on the range of the mean net length used within one fishing month.

• f_{LAT}: latitude effect as a level factor.

• $f_{\frac{\text{wet}}{\text{dry}}}$: 2-level factor for the south and north of the NEC.[6]

• r_{Grid}: random effects term for fishing grid-region.

• r_{ACN}: random effects term for fisher, identified by their ACN ACN), which accounts for the different capabilities of different boats and fishers.

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[6] Only considered for the North East Coast stock.

Appendix D - Historical Catch Data

The catch and effort history of the fishery is divided in time into three phases. The most recent is the CFISH logbook database phase. CFISH is a compulsory daily logbook database for commercial and charter fishers, and covers the period 1988-2017 for the considered stocks in Queensland. Prior to CFISH, the period covering 1981-1988, we refer to as the Tropical Research Assessment Program (TRAP) phase, which draws on voluntary research logbook data (GN01 and GN02) collated by the Tropical Resource Assessment Program (TRAP, see Gribble 2004). This is however only partially available for some stocks, as the East Coast benefits from this program only past 1984.

The earliest phase we term “historical” and it comprises a 1945–1980 reconstruction based on Queensland’s Fish Board data, available published literature and anecdotal evidence.

TRAP (1981 to 1988)

In the current assessment, we use data compiled by Lew Williams (DAF) in regions that approximately correspond to the spatial extent of the Southern and Northern Gulf of Carpentaria stock, as defined for the Status of Australian Fish Stocks report. These estimates were used for the years 1981 to 1988 and replace the commercial CFISH catch records to avoid misrepresentation.

On the East Coast, the TRAP data are available for the years 1985 to 1987. But excludes Broadsound, Shoalwater Bay and Stanage Bay of the Mackay stock region and all of the Central East Cast stock region. It will therefore be an underestimation. A normalized version using the ratio in CFISH data for 1989 and 1990 between Mackay grids and Broadsound grids to estimate catch for the missing 30-minute grid-regions is considered in the sensitivity analysis.

All east coast were include in the TRAP program except for the Central East Coast stock. To obtain catch estimates for the years 1981 to 1984 for any of these stocks, a linear increase was assumed based on the 1981 catch estimate based on the Fish board data, see details in next subsection on historical fish board catch.

The catch estimates for the Central East Coast for 1985 to 1987 were obtained by applying the ratio of the commercial Central East Coast catch and the total East Coast catch, averaged over the first five years in the CFISH logbook database, to the recorded East Coast TRAP catch.

Historical Fish Board (1945 to 1980)

Fishing in Queensland has occurred for a long time, being used for subsistence by indigenous and early European inhabitants. The first fishery to be developed after colonisation was the inshore fishery. The annual reports by harbours, which date back to the late 1800s, comment that ‘commercial fishermen disposed of their catch at the nearest population centres’. The main source of fishery catch data between 1930 and 1980 are figures published in the annual reports of the fish board responsible for marketing and distributing fish in Queensland during that period. It is uncertain what proportion of the total Queensland fisheries landings these figures represent due to local exports and black market sales. The Queensland Fish Board reports (held in full electronic form by the Department of Agriculture & Fisheries) record 61 market ‘categories’, assigned to the most likely current species. barramundi is one of these species. Monthly fisheries landings that passed through the Brisbane Fish Market from 1936 to 1945 are recorded by the annual reports, but do not indicate the point of origin of the landings. More location specific information is available from 1945, where the annual financial year landings from each depot are reported. The depot landings do not guarantee that landed fish was sourced from a particular area. For the purposes of analyses, we assume that the majority of the fish landed at a depot were caught in the nearby area.

For the Gulf, we additionally have a review by Dunstan (1959) that reports the total Gulf catch for 1955 as 22,389 lb and that in 1957, the total catch exported from the Gulf as approximately 200,000 lb headed and gutted fish, of which 70 per cent was barramundi. This equates to 9.85 tonnes and 87.75 tonnes whole wet weight in 1955 and 1957, respectively. The latter assumed 70 per cent barramundi, a conversion factor of 1.4 between headed-and-gutted fish to the whole wet weight and that the majority of the catch was taken from the Southern Gulf stock. We also assumed no expansion of the fishery between 1957 and 1970, but thereafter a rapid increase in the catch of barramundi, peaking in 1977, based on barramundi landings reported in Australian fisheries statistics. This and the assumption that most of the reported fish board catch in the Gulf was made in the Southern Gulf allowed for a coarse estimation of historical catch in the Gulf.

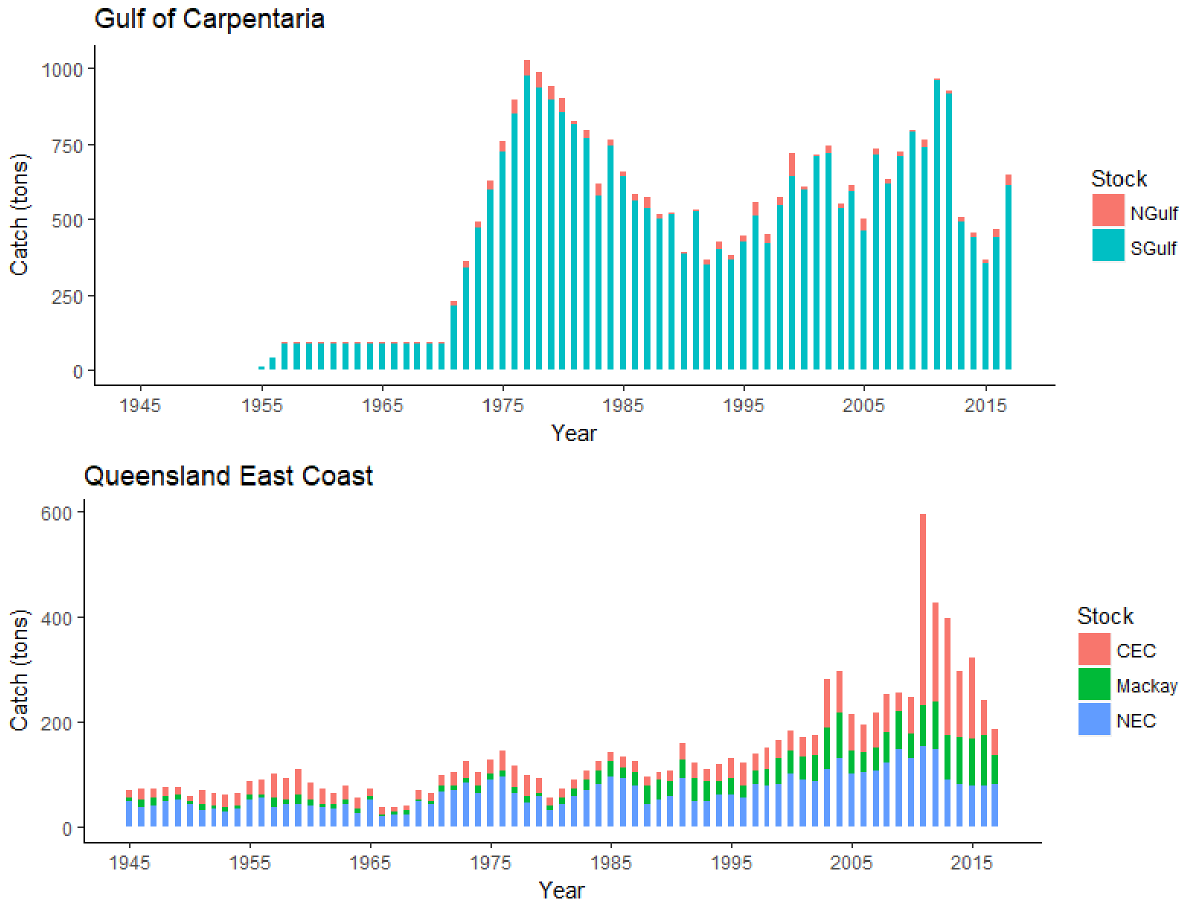

Figure 46: Estimated annual commercial catch of Queensland barramundi for: a) the Gulf of Carpentaria and b) Queensland east coast. The derived estimates for each stock were based on Fish Board historical estimates data (1945–1981), TRAP voluntary logbooks (Gulf: 1981–1987; EC: 1985–1987) and CFISH commercial logbooks (1988–2017; 1989–2017 for Gulf).

Appendix E - Contrast between historical (1945-1980) and CFISH data in Southern Gulf

It is important to flag the contrast between the estimated historical (1945–1980) catch data and the reported CFISH catch data (1988–2015). For the Southern Gulf catch, patterns in the CFISH logbook database (1989–2017) are not apparent in the estimated historical catch (1945–1980, Figure 47). Furthermore, the twelve years 1971 to 1982 involve two linear interpolations.

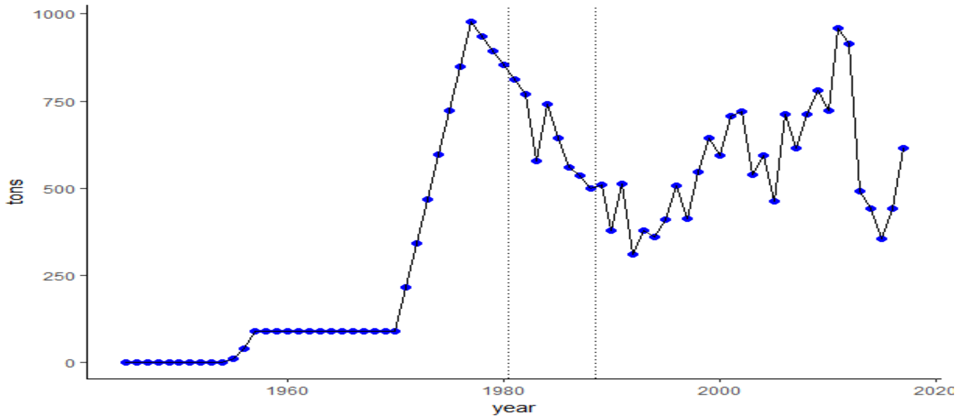

Figure 47: Commercial barramundi catch in Southern Gulf stock including reconstructed estimates 1954 to 1980, then TRAP data 1981 to 1988, before using CFISH logbook data 1989 to 2017.

Rough consistency in the minimum and maximum legal size limits applied during the period 1989-2017, made it reasonable to focus the modelling analyses on that period. This is also consistent with the approach taken in Campbell *et al*., (2008). Having said that, some analyses also considered the combined data sources spanning the entire period 1945-2017. However, these did not yield credible results see Figure 48. It should be noted that the current model under base case conditions assumed the catchability parameter q was constant, whereas Campbell et al. 2017 fitted a catchability parameter q that increased over time.

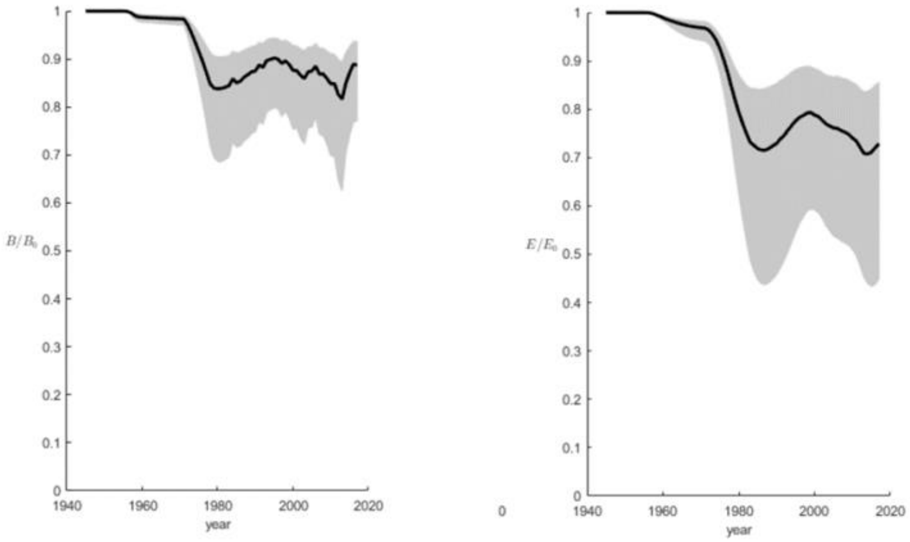

Figure 48: Estimated reference points ($B/B_0 \; and \; E/E_0$) using estimated historical catch for the Southern Gulf barramundi stock.

Appendix F - Parameter estimates

Table 15 lists the model estimated parameters (median, with standard deviation in parentheses) from the MCMC analysis. The steepness parameter h and the biomass to virgin biomass ratio in 1988 for the East Coast and 1989 for the Gulf, denoted by ψ (i.e., initial depletion) were fixed input parameters. To compactly report on the recruitment vector ϵ_t, the mean of the median over the MCMC iterates is reported.

Table 15: Fitted median parameter values for the base case population model for each barramundi stock. Standard deviations are provided in parentheses.

Stock	R_0	B_0^t	h^*	L_∞	k	a_0	σ	ψ^*	$\sum \epsilon_t / T$	$\hat{\sigma}$
SGulf	$1.3 \cdot 10^6$	35254	0.7	1297	0.18	-0.466	113	0.2	-0.208	0.830
	($2.1 \cdot 10^5$)	*(4299)*		*(92)*	*(0.022)*	*(0.018)*	*(8.3)*		*(0.658)*	*(0.160)*
NGulf	$4.4 \cdot 10^4$	828	0.7	1208	0.17	-0.341	81	0.02	-	-
	($1.3 \cdot 10^4$)	*(101)*		*(106)*	*(0.021)*	*(0.028)*	*(41)*			
NEC	$6.6 \cdot 10^4$	1946	0.7	1326	0.19	-0.452	88	0.25	0.043	*0.149*
	($1.3 \cdot 10^4$)	*(56)*		*(83)*	*(0.008)*	*(0.017)*	*(36)*		*(0.306)*	*(0.100)*
Mack	$8.1 \cdot 10^4$	1815	0.7	1239	0.17	-0.364	80	0.25	-0.0002	0.001
	($4.1 \cdot 10^3$)	*(187)*		*(188)*	*(0.020)*	*(0.028)*	*(46)*		*(0.026)*	*(0.004)*
CEC	$4.5 \cdot 10^4$	1859	0.7	1549	0.17	-0.411	85	0.25	0.001	0.001
	($7.0 \cdot 10^4$)	*(152)*		*(154)*	*(0.022)*	*(0.026)*	*(20)*		*(0.100)*	*(0.002)*

* fixed at stated value; ^{t} total virgin biomass

Table 16: Southern Gulf barramundi stock fitted median parameter values under alternate model scenarios.

SGulf	R_0	B_0^t	h^*	L_∞	k	a_0	σ	ψ^*	$\sum \epsilon_t / T$	$\hat{\sigma}$
Base case	$1.3 \cdot 10^6$	35254	0.7	1297	0.180	-0.466	113	0.2	-0.21	0.83
ψ_{low}	$1.5 \cdot 10^6$	37778	0.7	1245	0.184	-0.472	115	0.1	-0.23	0.84
ψ_{high}	$1.2 \cdot 10^6$	33833	0.7	1314	0.176	-0.472	112	0.3	-0.06	0.77
q_{inc}	$1.3 \cdot 10^6$	34742	0.7	1280	0.178	-0.477	113	0.2	-0.30	0.09
Const rec-catch	$1.3 \cdot 10^6$	35721	0.7	1288	0.179	-0.480	113	0.2	-0.17	0.82
Prop rec-catch	$1.3 \cdot 10^6$	35950	0.7	1286	0.180	-0.472	113	0.2	-0.18	0.81

* fixed at stated value; ^{t} total virgin biomass

Table 17: Northern Gulf barramundi stock fitted median parameter values under alternate model scenarios.

NGulf	R_0	B_0^t	h^*	L_∞	k	a_0	σ	ψ^*
Base case	$4.4 \cdot 10^4$	828	0.7	1208	0.170	-0.341	81	0.02
ψ_{low}	$3.2 \cdot 10^4$	905	0.7	1331	0.181	-0.331	159	0.10
ψ_{high}	$5.6 \cdot 10^4$	859	0.7	1150	0164	0.000	49	0.30
q_{inc}	$2.9 \cdot 10^4$	776	0.7	1319	0.178	-0.331	148	0.20
Const rec-catch	$5.4 \cdot 10^4$	986	0.7	1128	0.192	-0.339	17	0.20
Prop rec-catch	$9.9 \cdot 10^4$	836	0.7	818	0.158	-0.373	192	0.20

* fixed at stated value; ^{t} total virgin biomass

Table 18: North East Coast barramundi stock fitted median parameter values under alternate model scenarios.

NEC	R_0	B_0^t	h^*	L_∞	k	a_0	σ	ψ^*	$\sum \epsilon_t / T$	$\hat{\sigma}$
Base case	$6.6 \cdot 10^4$	1946	0.7	1326	0.19	-0.453	88	0.25	0.043	0.150
ψ_{low}	$7.6 \cdot 10^4$	1971	0.7	1239	0.195	-0.462	106	0.15	0.160	0.190
ψ_{high}	$6.2 \cdot 10^4$	1923	0.7	1356	0.190	-0.432	60	0.35	0.050	0.130
q_{inc}	$6.1 \cdot 10^4$	1960	0.7	1280	0.178	-0.478	113	0.25	0.061	0.150
Const rec-catch	$2.2 \cdot 10^4$	1944	0.7	1990	0.197	-0.122	118	0.25	0.421	0.254
Prop rec-catch	$7.8 \cdot 10^4$	1981	0.7	1229	0.197	-0.472	15	0.25	0.328	0.267

* fixed at stated value; ^{t} total virgin biomass

Table 19: Mackay barramundi stock fitted median parameter values under alternate model scenarios.

Mack	R_0	B_0^t	h^*	L_∞	k	a_0	σ	ψ^*	$\sum \epsilon_t / T$	$\hat{\sigma}$
Base case	$8.1 \cdot 10^4$	1815	0.7	1239	0.170	-0.365	80	0.25	-0.0002	0.001
ψ_{low}	$5.1 \cdot 10^4$	1903	0.7	1457	0.183	-0.366	144	0.15	0.002	0.001
ψ_{high}	$1.4 \cdot 10^5$	1870	0.7	1097	0.156	-0.321	44	0.35	0.050	0.13
q_{inc}	$3.5 \cdot 10^4$	1910	0.7	1684	0.186	-0.360	150	0.25	0.0003	0.001
Const rec-catch	$9.5 \cdot 10^4$	1830	0.7	1187	0.185	-0.373	40	0.25	0.001	0.001
Prop rec-catch	$10 \cdot 10^4$	1870	0.7	1153	0.180	-0.333	44	0.25	0.0003	0.001

* fixed at stated value; ^{t} total virgin biomass

Table 20: Central East Coast barramundi stock fitted median parameter values under alternate model scenarios.

CEC	R_0	B_0^t	h^*	L_∞	k	a_0	σ	ψ^*	$\sum \epsilon_t / T$	$\hat{\sigma}$
Base case	$4.5 \cdot 10^4$	1859	0.7	1549	0.170	-0.412	85	0.25	0.001	0.001
ψ_{low}	$3.7 \cdot 10^4$	1854	0.7	1666	0.174	-0.379	111	0.15	0.001	0.001
ψ_{high}	$5.6 \cdot 10^4$	1837	0.7	1425	0.177	-0.424	57	0.35	0.001	0.001
q_{inc}	$3.0 \cdot 10^4$	1892	0.7	1795	0.176	-0.381	111	0.25	0.0001	0.001
Const rec-catch	$5 \cdot 10^4$	1887	0.7	1480	0.183	-0.404	76	0.25	0.001	0.001
Prop rec-catch	$5.2 \cdot 10^4$	1894	0.7	1464	0.182	-0.401	76	0.25	0.001	0.001

* fixed at stated value; ^{t} total virgin biomass