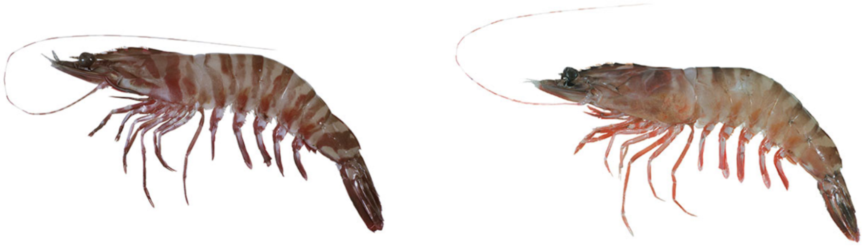

Stock assessment of Queensland east coast tiger prawns (*Penaeus esculentus* and *Penaeus semisulcatus*)

2020

Queensland
Government

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Contents

Summary

‘Tiger prawn’ is a collective term for two species: brown tiger prawn (*Penaeus esculentus*) and grooved tiger prawn (*P. semisulcatus*). Brown tiger prawns are endemic to tropical and subtropical waters of Australia, while grooved tiger prawns have a wider Indo–West Pacific distribution.

Tiger prawns in Queensland are predominantly caught by trawl and are part of the East Coast Otter Trawl Fishery. There are two management regions within the east coast fishery: the northern region and the central region. For management purposes each region was assessed separately.

A stock assessment model was used to assess the population status of tiger prawn in each region. The assessments were an update on the previous assessments conducted in 2010 (Wang 2015), and incorporated revised harvest, catch rate and gear data. The updated assessments included harvest data from 1941 to 2019, and catch rate and gear data from 1988 - 2019. A delay difference model was applied with monthly time steps. The key population performance indicator was an annual estimate of exploitable biomass.

Harvest data from 1941 were assumed, for modelling purposes, to represent the commencement of significant fishing mortality (i.e. near virgin state of tiger prawns). Historical data for the years 1941–1981 (inclusive) was based on an internal report (“Documentation of Qld Fish Board Data”). Estimates for the years 1982–1987 inclusive, were guided by the internal report and commercial logbook (CFISH) data. Harvest data from the years 1988–2019 (inclusive) was from CFISH data.

The 2019 harvest in the northern region was 602 tonnes, and in the central region was 333 tonnes (Figure 1, Table B.1). In the northern region the average harvest for the last five years was 832 tonnes, ranging between 602 and 1023 tonnes (Table B.1). In the central region the average harvest for the last five years was 303 tonnes, ranging between 146 and 396 tonnes.

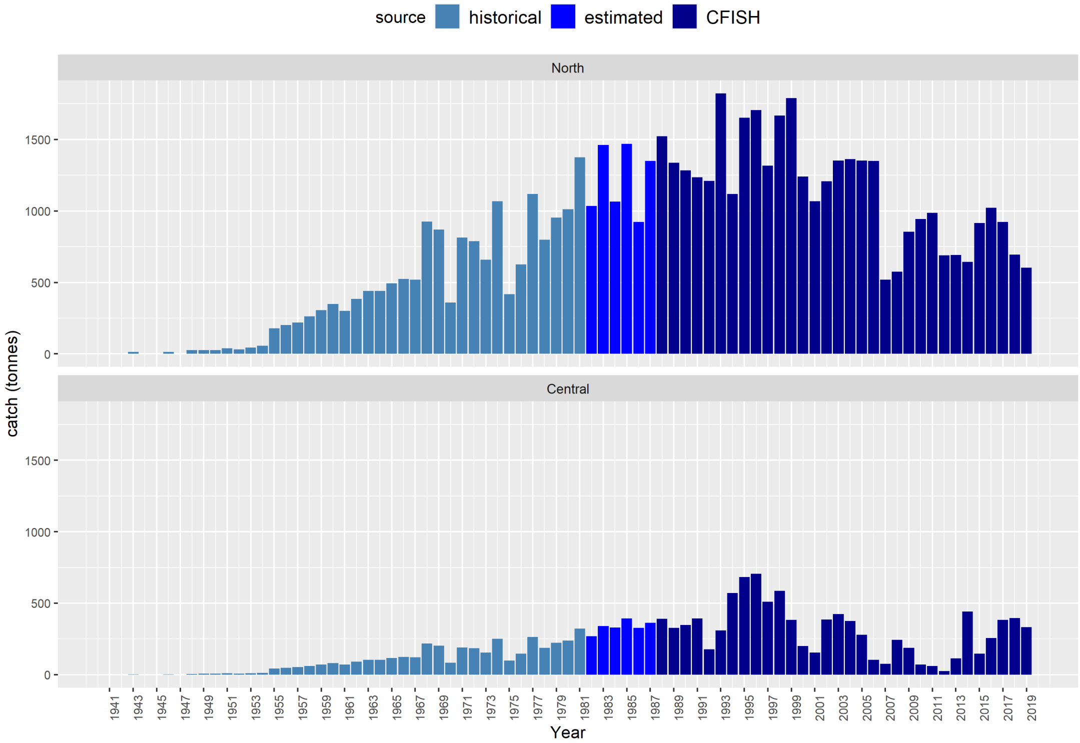

Figure 1 Total annual estimated landed catch of tiger prawns from 1941 to 2019 for the northern and central regions

Commercial catch rates were standardised and used to fit the stock assessment model (Figure 2). Standardised catch rate analyses were estimated separately for the northern region and central region. The explanatory terms were year, month, lunar cycle, hours fished, vessels as a random effect, and annual changes in fishing power offset. The unit of operation was defined to be a single day of fishing by each vessel (referred to as 'boat-day').

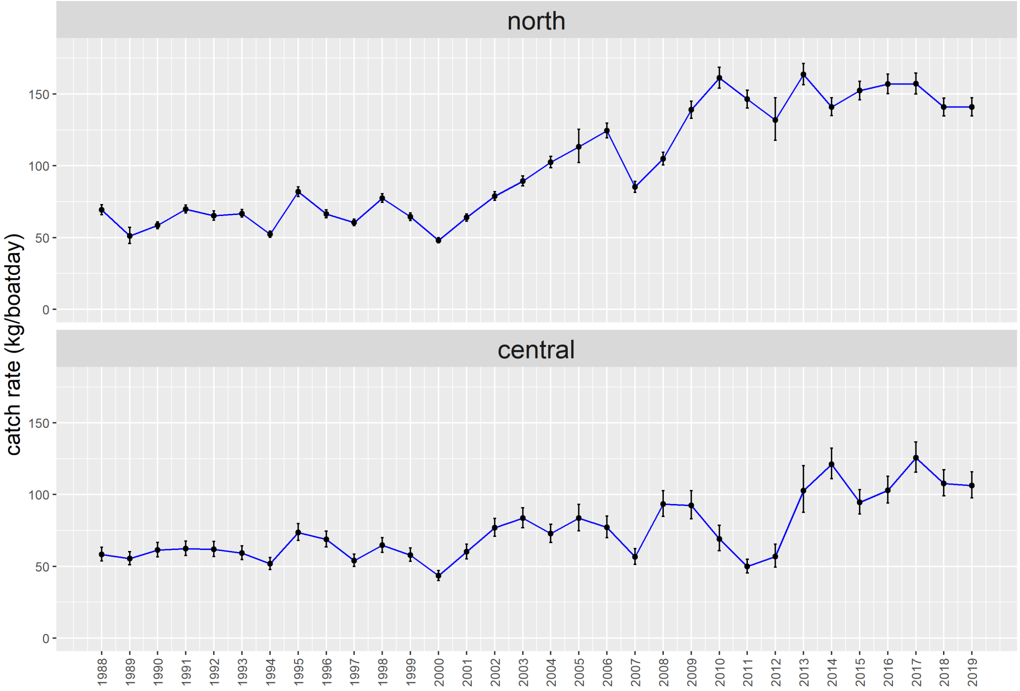

Figure 2 Monthly standardised catch rates (with 95% confidence intervals) for the northern region and central region.

The stock assessment evaluated results against the target biomass (B_{targ}) of 60% of the biomass at the start of the fishery. This is defined in Queensland's Sustainable Fisheries Strategy 2017–2027 (Department of Agriculture and Fisheries 2017). The assessment estimated that the 2019 biomass ratio in the northern region was 49% of the unfished 1941 level and in the central region was 50% (Figure 3).

Figure 3 Annual tiger prawn biomass relative to unfished biomass (1941) for northern region and central region

Tiger prawns are an effort managed fishery where fishing levels are adjusted in order to achieve the target biomass. For this, the draft Harvest Strategy Policy commits to a "hockey stick" harvest control rule to determine effort levels that aim to build or maintain stocks to a target level. This control rule applies the 20:60:60 rule which recommends fishing effort at an optimum E_{targ} level for stocks at or above 60%, or reduced effort aligned with stock biomass between 60% and 20%, or no fishing for stocks below 20%.

Recommendations

In the northern tiger prawn region the assessment estimates that the 2019 biomass ratio was 49% of the unfished biomass. The standardised fishing effort in this region in 2019 was 3874 boat days. The recommended effort to build the stocks to the 60% biomass ratio target reference point is 3824 boat days. In the central tiger prawn region the assessment estimates that the 2019 biomass ratio was 50% of the unfished biomass. The standardised fishing effort in this region in 2019 was 2986 boat days. The recommended effort to build the stocks to the 60% biomass ratio target reference point is 1276 boat days.

The fishing effort recommendations were based on the target biomass (B_{targ}) of 60%, and the 2019 exploitable biomass ratio being 49% in the northern region and 50% in the central region, both below the target biomass of 60% (Table 1).

Table 1 Current and target indicators—target reference point for biomass (exploitable biomass) ratio is 60%

Parameter	**Estimate**
Northern Region	
Exploitable biomass ratio in 2019 (B_{2019}/B_{1941})	49%
Exploitable biomass ratio at MSY	34%
2019 harvest	602 tonnes
Maximum sustainable yield (MSY)	1216 tonnes
Maximum yield at B_{targ}	978 tonnes
Fishing effort in 2019: standardised	3874 boat-days
Fishing effort: recommended from the 20:60:60 harvest control rule	3824 boat-days
Fishing effort for B_{MSY} (E_{MSY} for mean 2015–2019 fishing power)	10 911 boat-days
Fishing effort for B_{targ} (E_{targ} for mean 2015–2019 fishing power)	5235 boat-days
Central Region	
Exploitable biomass ratio in 2019 (B_{2019}/B_{1941})	50%
Exploitable biomass ratio at MSY	36%
2019 harvest	333 tonnes
Maximum sustainable yield (MSY)	311 tonnes
Maximum yield at B_{targ}	252 tonnes
Fishing effort in 2019: standardised	2986 boat-days
Fishing effort: recommended from the 20:60:60 harvest control rule	1276 boat-days
Fishing effort for B_{MSY} (E_{MSY} for mean 2015–2019 fishing power)	3443 boat-days
Fishing effort for B_{targ} (E_{targ} for mean 2015–2019 fishing power)	1686 boat-days

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The authors acknowledge the fishers and scientists who have contributed to past research on tiger prawn, particularly Na Wang and Clive Turnbull.

Glossary

DAF	Department of Agriculture and Fisheries (Queensland)
GBRMPA	Great Barrier Reef Marine Park Authority
CFISH	Queensland commercial fishery information system (logbook database)
Fishing year	1 January to 31 December
GPS	global positioning system
BRD	bycatch reduction device
TED	turtle exclusion device
MSY	maximum sustainable yield
CI	confidence interval
B_0	unfished biomass (biomass is exploitable biomass in this assessment ExB_0)
E_{MSY}	effort at maximum sustainable yield
B_{MSY}	biomass at MSY, (biomass is exploitable biomass in this assessment)
B_{MEY}	biomass at MEY, (biomass is exploitable biomass in this assessment
B_{targ}	target reference point for biomass, (biomass is exploitable biomass in this assessment)

1 Introduction

'Tiger prawn' is a collective term for two species: brown tiger prawn (*Penaeus esculentus*) and grooved tiger prawn (*P. semisulcatus*). Brown tiger prawns are endemic to tropical and subtropical waters of Australia, while grooved tiger prawns have a wider Indo–West Pacific distribution (Ward et al. 2006). Female brown tiger prawns mature around 21–28 mm carapace length at around six months of age, and female grooved tiger prawns mature around 28–29 mm carapace length at around six months (Wang 2015).

Fishing for tiger prawns in Queensland predominantly occurs in the northern and central regions within the East Coast Otter Trawl Fishery. This report focuses on tiger prawn stocks within each of the two trawl management regions.

Tiger prawns are a valuable commercially-fished stock, with harvests at approximately 1400 tonnes annually in the last five years, and with a total annual landed value of about AUD$21 million in 2017–18 (Australian Bureau of Agricultural and Resource Economics and Sciences 2018). Management in Queensland applies a range of input controls including vessel entry limitations, boat-day/effort-unit allocations, vessel and gear size restrictions and spatial-seasonal closures.

Table 1.1 Management changes applied to East Coast Otter Trawl Fishery and tiger prawn stocks in Queensland

Year	Fisheries Management, Regulations and Operations
1980	1400 licensed vessels
1988	Compulsory commercial catch logbook reporting commenced
1999	Introduction of East Coast Trawl Management Plan Commencement of reduction of licence operators. Over the course of a few years licence operators were reduced from 1400 to 800
2000	Introduction of southern trawl closure from 20 September to 1 November
2001	Revised Plan: buy back and effort management system, effort unit trading system Introduction of an effort management system based on effort nights
2002–2003	Increase in average boat size due to smaller boats (i.e. 10–40 hull units) leaving the fishery as a result of licences being bought out by the government buyback scheme
2004	Reduction of licensed operators to 527 vessels Commencement of compulsory commercial logbook reporting of gear Vessels use of computer mapping and global positioning systems Use of bycatch reduction devices and turtle exclusion devices Representative Areas Programme (RAP) 1 July: comprehensive rezoning of the whole Great Barrier Reef; additional areas of the Great Barrier Reef closed to trawl fishing

In order to inform the levels of effort that will sustain the stock there is a need to undertake a stock assessment. An important consideration of assessments in effort-based management is to account for increased efficiency in the fishing fleets. As with previous assessments, fishing power has been included in this assessment as it had been reported to have increased by 18% from 1988 to 2013 (Wang 2015) with the greatest increase between 1992 and 2000.

Previously, a weekly delay-difference model was applied using data from 1988 to 2013 (Wang 2015). The previous assessment estimated that the MSY for tiger prawn in northern region was 1107 t, in the south (Great Barrier Reef Marine Park, GBRMP, 24°–16°S) was 728 t and for brown tiger prawn in Moreton Bay was 197 t (Wang 2015). Catches from these areas prior to 2000 were above the estimated MSY, thereby reducing the spawning stock biomass to 80–90 per cent of estimated B_{MSY}, (Wang 2015). The term ‘spawning stock’ biomass was also used however it is not clear if this was meant to be exploitable biomass.

The current assessment is an update on the previous delay difference assessment of the Queensland stock of tiger prawns, conducted in 2014 (Wang 2015). The assessment incorporated updated commercial catch, effort, gear and vessel data to determine the effect of known increases in efficiency in fishing fleets. The model assessed tiger prawns recruited to offshore waters and excluded juveniles harvested from estuaries and from the Moreton Bay region. Tiger prawns are generally not harvested in estuaries. They are harvested in Moreton Bay, which is a very large estuary, but in north Queensland they are not really an estuarine species.

This report presents estimates of sustainable harvests and effort to provide advice needed to manage the fishery at sustainable levels, and support the goals defined in *Queensland Sustainable Fisheries Strategy: 2017-2027* (Department of Agriculture and Fisheries 2017) and the Status of Australian Fish Stocks framework (`fish.gov.au`). The goals of the Sustainable Fisheries Strategy, are to set sustainable harvest or fishing limits to achieve 40–50% biomass by 2020. By 2027, sustainable harvest or fishing limits will be set to achieve maximum economic yield or 60% biomass.

2 Methods

2.1 Spatial stratification

There are two management regions for tiger prawns within the East Coast Otter Trawl Fishery that required assessment: the northern region and the central region (Figure 2.1). Two assessments were conducted, one for each region, and presented in this report. Each region was further subdivided into areas where the majority of fishing occurs and the data from these specific areas (Figure 2.1) were used in the analysis of catch rates and fishing power.

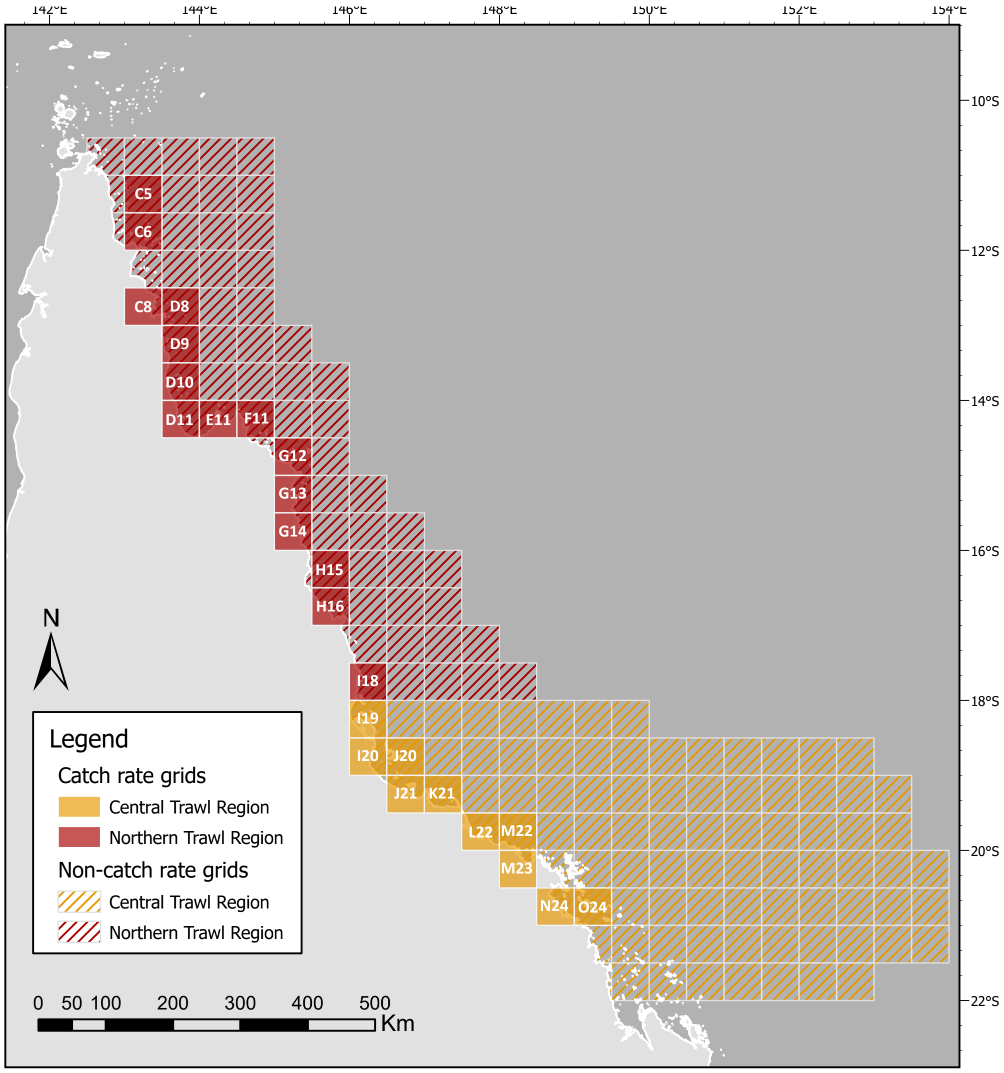


Figure 2.1 Two Queensland east coast trawl regions, northern region and central region, showing the grids where the majority of the catch occurs and used in the standardise catch rate analysis.

2.2 Data sources

The data sources included in this assessment (Table 2.1) were used to determine catch rates, and to create total annual and monthly harvests. The time series of catch data was 78 years from 1941 to 2019 however only data from CFISH log book records (spanning between 1988 to present) were the only data based on empirical data collection. Catch estimates before 1988 were based on an internal report ("Documentation of Qld Fish Board Data").

Table 2.1 Data compiled for input into the population model

Data	Years	Source
Commercial	1988–2019	CFISH – Logbook catch effort data collected by Fisheries Queensland
	1988–2004	Survey – gear data collected by Fisheries Queensland
	2004–2020	Logbook – gear data collected by Fisheries Queensland
	1941–1981	QFISH – catch data
Lunar	January 1991–December 2019	O'Neill et al. (2014) – continuous daily luminous scale of 0 (new moon) to 1 (full moon)

Commercial catch and effort data were sourced from the Queensland Fisheries compulsory logbook records (CFISH), which began in 1988. The Queensland data contained daily entries for each boat for harvest in kilograms, the geographic location (30' grids) and the gear and vessel characteristics within the trawl fishery (Table 2.1, Table A in the Appendix).

The gear and vessel fields used were otter boards, net type, gear type, bycatch reduction devices and turtle excluders (BRD and TED), computer mapping, fuel capacity, fuel use, ground chain (mm), global positioning systems (GPS), engine rated power (hp), vessel length, mesh size, net size, propeller nozzle, propeller pitch, propeller diameter, reduction, sonar, speed, and the use of try gear.

2.3 Harvest estimates

For modelling purposes harvest data from 1941 were assumed to represent the commencement of significant fishing mortality (i.e. near virgin state of tiger prawn). Harvest data were collected differently along the entire time period between 1941 to 2019 with essentially three time periods: historical catch (1941–1980, internal report "Documentation of Qld Fish Board Data"), estimated catch, where there was no catch data (1981 to 1987 inclusive) and logbook catch (1988 to current year, 2019 CFISH data, Table 2.1). Historical commercial harvest data between 1941–1981, were obtained from an internal report (Documentation of Qld Fish Board Data). The data had to be reconstructed because all the catch landings were aggregated into one homogenous 'prawns' group and not segregated into species or area and CFISH logbook data was used as a guide to obtain estimates of historical harvest. This was achieved by estimating the proportion of spatial split between each of the two trawl regions and the species split within each area. These proportions were applied to the data presented in the internal report. Area by month harvest estimates for 1941–1981 were obtained as follows:

- use first five years of CFISH logbook data to determine proportion of prawn catch in each of the northern and central regions
- within each region obtain the proportion of prawn catch that is tiger prawns (*P. semisulcatus* and *P. esculentus*)
- apply these proportions to the 'prawn' aggregate of catch in historical data
- use first five years of CFISH logbook data to determine proportion of prawn catch in each month
- use these proportions to translate the annual catches into monthly catches in the annual historical time series

There is no harvest information between 1981 - 1987 inclusive, and data had to be estimated (Figure 1, Table B.1). The catches obtained in the last two years of the fishboard data (1980–1981) were applied repeatedly between 1982–1987 with noise added (using the jitter function in R software and taking the absolute values).

Collectively, these annual harvest entries were reconstructed into monthly estimates, and used as an input to the assessment to generate a continuous time series of historical catch dating back to 1941.

2.4 Fishing power estimates

Fishing power estimates were based on Queensland trawl logbook data consisting of daily catch and effort information per vessel (2004–2019), and combined survey of gear usage and vessel information (1988–2004) . The estimates of fishing power were from 30’ x 30’ grids within each trawl region (Figure 2.1).

Fishing power was estimated using a linear mixed model with REML in GenStat software (VSN International 2019). Prior to estimating fishing power, a collinearity check was conducted to determine which variables were related of all the variables considered (otter boards, net type, gear type, BRDs and TEDs, computer mapping, fuel capacity, fuel use, ground chain (mm), GPS, engine rated power (hp), vessel length, mesh size, net size, propeller nozzle, propeller pitch, propeller diameter, reduction, sonar, speed, the use of try gear). Any variables that were related cannot all be fitted simultaneously, and therefore only one of those variables was selected to be used in the subsequent linear mixed model.

As a result, five variables were included in the estimation of fishing power:

- engine rated power
- net type
- ground gear
- nozzle
- speed

Fishing power and gear effects were estimated for each of the two trawl regions considered in this report.

The following model was used to obtain coefficients for each gear and vessel term for subsequent calculations of fishing power:

$$log_e(C_{\text{ivayml}}) = \beta_0 + X\alpha + Z\gamma + \epsilon \tag{2.1}$$

where C_{ivayml} was the catch taken on day i by the v^{th} vessel in grid a, during fishing year y, month m and lunar cycle l; parameter β_0 was a scalar intercept; α a matrix of fixed parameter terms including β_1, β_2, β_3 and β_4, multiplied by data X (X_1, X_2, X_3 and X_4); γ a vector of random vessel terms with data Z; ϵ the normal error term. Vectors β_1, β_2, β_3 and β_4 were parameters for abundance, lunar phase, hours fished and catchability, respectively. The abundance vector β_1 included terms for the two-way interactions of fishing year, month, and grid square. The vector β_2 consisted of a parameter term for lunar luminance and lunar advance. The catchability vector β_4 included parameters for vessel characteristics: engine rated power, net type, otter boards, gear type, use of try-gear, bycatch reduction devices and turtle excluders, and global positioning systems, some of which were categorical and others continuous. Natural logarithm transformations were applied to continuous X_2 and X_4 variate data.

All statistically significant parameter estimates from the regression model were used to calculate annual changes in average relative fishing power. One of the outputs of the REML analysis was parameter estimates for each variable and each level within a factor (catchability coefficients). The catchability coefficients for each gear and vessel terms were multiplied by their corresponding gear and vessel data:

$$\text{Catchability coefficient}_g = X_g \beta_g \tag{2.2}$$

where β_g is the coefficient for each gear and vessel term (g) and X_g is the data for each gear and vessel term (g). This was applied for each data record in the model.

The catchability coefficient was summed across all gear and vessel terms to obtain a total fishing power estimate (summed over all gear and vessel terms combined). This total fishing power estimate was then averaged for each fishing year and trawl region to obtain mean annual estimates of fishing power for each area on the log scale.

Following this, the estimates of fishing power were summarised for each year, and expressed as a proportional change relative to 1989, the base reference fishing year as reported by O'Neill et al. (2003).

Relative fishing power (F_{yz}) within each trawl region was thus defined using Equation 2.3:

$$Fp_{yz} = \exp\left(\text{fp}_{yz} - \text{fp}_{1989\,z}\right) \tag{2.3}$$

where y is year and z is trawl region, fp_{yz} is annual fishing power on the log scale and F_{yz} is relative fishing power.

2.5 Abundance indices

2.5.1 Commercial standardised catch rates

Standardised catch rate analyses were carried out separately for the northern region and the central region. For the northern region, 15 grids were selected for catch rate standardisation (Figure 2.1), and for the central area, 10 grids were selected. Grids were based on where most of the harvest occurred. The fishing years were defined and labelled from month January (1) to December (12).

Standardised catch rates were calculated using REML in Genstat using linear mixed models (REML) and assumed normally distributed errors on the log scale (VSN International 2019).

The following model was used:

$$\log(\text{catch}_{\text{fp}}) \sim \text{year} * \text{month} + \text{lunar} + \text{lunar}_{\text{adv}} + \text{loghrs} + \text{random} = \text{vessel} \tag{2.4}$$

where $\log(\text{catch}_{\text{fp}})$ is the log of the catch adjusted for fishing power. Fishing year (year) and fishing month (month) relate to the fishing season for tiger prawns which is the same as the calendar year. Lunar is the luminosity of the moon, lunar advance ($\text{lunar}_{\text{adv}}$) differentiates whether the lunar phase was waxing or waning, and (loghrs) is the log of the hours fished per boat per day.

The analysis estimated the annual gear fishing power trend X_2 for β_2 (Table 2.2). Standardised catch rates were predicted from the two-way β_1 interaction term, which provided abundance indices for each fishing year and month. Catch rates were predicted relative to the pre-estimated level for vessel identification (for method refer to Courtney et al. (2014))

Table 2.2 Linear mixed models (REML) used to standardise catch rates

	Analysis
Years	1989 to 2019
Fixed terms	$\beta_0 + X_1\beta_1 + X_2\beta_2 + X_3\beta_3 + X_4\beta_4$
Random terms	$Z_1\gamma_1 + Z_2\gamma_2$
Fishing power offset	tiger log fishing power from β_2
Predictions	β_1

2.6 Effort

Effort (in boat-days) was estimated following the general equation

$$\text{Effort} = \text{harvest}/\text{catchrate} \tag{2.5}$$

where harvest was the annual catch or (in the case of harvest targets) the equilibrium catch (i.e. predicted by the model) for each reference point (B_{MSY} or B_{targ}) and catch rate was the standardised catch rate (see section 2.5). However to estimate the effort for the reference points (effort at B_{MSY} or B_{targ}) the catch rate used in Equation 2.5 was the fitted catch rate which was the output from the model instead of the standardised catch rate.

2.7 Biological parameters

The biological information and parameters relevant for the delay difference model are detailed in (O'Neill et al. 2005). Most of these parameters have been used again for this assessment (Table 2.3). The only updated parameter was the Brody growth coefficient

2.7.1 Growth

Growth in mean body weight at age follows the recursive Ford-Brody equation (Equation 2.6, (Hilborn et al. 1992). For tiger prawns, the age a is defined in terms of months.

$$w_{a+1} = \alpha + \rho w_a \tag{2.6}$$

where a is age, and α and ρ are fitted constants over the ages $a = r - 1,\ r,\ \ldots,$ where r is the age at recruitment to the fishery, and w_a is the weight at age of recruitment into the fishery (four months). The constants α and ρ were obtained by fitting to the von Bertalannfy growth model (Equation 2.8)

The Brody growth coefficient ρ is estimated as follows

$$\rho = \frac{w_a - W_\infty}{w_{a-1} - W_\infty} \tag{2.7}$$

where W_∞ is based on the L_∞ estimated from the length based von bertalanffy equation (Equation 2.8) then converted to weight (Equation 2.9)

$$L_t = L_\infty(1 - \exp(-k(t - t_0))) \tag{2.8}$$

where L_t is the length at age t, L_∞ is the asymptotic maximum length, k is the growth coefficient, and t_0 is the time (age) at length zero. The parameters for L_∞ were 44.8, and 37.4 mm (carapace length), for

P.semisulcatus (female and male respectively), and 62.2 and 38.1 mm (carapace length) for *P.esculentus* (female and male respectively). The parameters for k were 0.164 and 0.137 for *P. esculentus* (female and male respectively), and 0.1 and 0.254 for *P. semisulcatus* (female and male respectively)

$$W_L = \alpha L^b \tag{2.9}$$

where W_l is weight to length and α and b are constants.

The Brody growth coefficient ρ was estimated separately for females and males of the brown tiger prawn and the grooved tiger prawn. A single parameter for ρ was then selected based on an approximation of the two species and sexes combined.

2.8 Population model

A delay difference model was used that operated on a monthly time step t (Equation 2.10)

$$B_t = (1+\rho)B_{t-1}s_{t-1} - \rho s_{t-1}s_{t-2}B_{t-2} - \rho s_{t-1}w_{r-1}R_{t-1} + w_r R_t \tag{2.10}$$

where B_t was the exploitable biomass of tiger prawns (kg), ρ was the Brody growth coefficient estimated outside the model, s_t was prawn survival $\exp(-M)(1 - \text{Catch}_t/B_t)$ and reflects the combined effects of natural and fishing mortality (a time varying harvest rate defined by Catch_t/B), r was the age at recruitment, w_a was the mean weight of prawns at age a (in kg) and R_t was the number of newly recruited prawns. (Table 2.3). For a description of the delay difference model refer to (Deriso 1980; Hilborn et al. 1992).

2.8.1 Population dynamics

The general population model was introduced in the above section and following are details that relate to tiger prawns in Queensland. As mentioned the dynamics of the delay difference model tracked numbers (N) biomass (B) and recruitment in every month (t) (O'Neill et al. 2005). Biomass was the total biomass of age r and older animals before harvest was applied. The current model assumes that tiger prawns recruit at four months which is two months prior to maturity at six months. Therefore monthly recruitment is the number of prawns reaching age r (four months).

Recruitment numbers — Beverton-Holt formulation

Recruitment numbers (R) was assumed to follow an annual Beverton and Holt function with lognormal deviations. The model was firstly initialised to generate and unfished stock in equilibrium using virgin recruitment (R_0), estimated on the log scale using the parameter R_{init} (Equation 2.11). After the model was initialised a series of equations were used to estimate annual and monthly recruitment numbers over the current time series of the fishery (1941 - 2019).

- estimate steepness h using ξ (Equations 2.12 and 2.13)
- estimate the number of female tiger prawns spawning each year (S_y, Equation 2.14)
- use steepness h and virgin recruitment (R_0) and the number of female spawners S_y to estimate α and β (Equation 2.15)
- use α, β in the Beverton Holt stock recruitment equation to estimate annual recruitment (Equation 2.16)

- finally, obtain estimates of monthly recruitment (Equation 2.17), by multiplying annual recruitment with a monthly recruitment probability vector (Table B.2) calculated from a normalised von Mises directional distribution (Mardia et al. 2009).

$$R_0 = \exp\left(R_{\text{init}}\right) \times 10^8 \tag{2.11}$$

$$r_{\text{max}} = 1 + \exp\left(\xi\right) \tag{2.12}$$

$$h = r_{\text{max}}/(4 + r_{\text{max}}) \tag{2.13}$$

$$S_y = 0.5 \sum_{t=1}^{12} \theta \frac{1 - \exp(-Z_t)}{Z_t} N_t \tag{2.14}$$

$$\begin{aligned} \alpha &= \frac{S_0(1-h)}{4hR_0} \\ \beta &= \frac{5h-1}{4hR_0} \end{aligned} \tag{2.15}$$

where Z_t was the monthly total mortality and N_t is the exploitable population number of tigers. The proportion spawning each month was provided by θ (Table B.2).

The number of annual recruits from the Beverton-Holt equation was

$$\text{rec}_y = \frac{S_y}{\alpha + \beta S_y} \tag{2.16}$$

Finally, the number of monthly recruits was

$$R_t = \text{rec}_y \phi_t \epsilon_y \tag{2.17}$$

where y is the fishing year, S_y is the number of (monthly) female spawners summed over the year, ϵ_y is the annual recruitment deviation, α and β are the Beverton-Holt parameters (Beverton et al. 1957), R_t is the final number recruiting taking into account proportion recruiting (ϕ_t refer to Table B.2 source is (O'Neill et al. 2005)). The parameters R_{init}, ξ and ϵ_t are estimated by the model. A penalty function was applied to the ξ parameter to prevent unrealistically high values of steepness (resulting in high stock recruitment/productivity), and a bound was applied to R_{init} to prevent unrealistically high biomass levels.

Harvest rate

In the population model, harvest rate is used instead of instantaneous fishing mortality, to account for time varying fishing mortality (Hilborn et al. 1992) and is simply the observed catch divided by predicted biomass (Equation 2.18)

$$u_t = C_t/B_t \tag{2.18}$$

where C_t is the monthly catch (kg) and B_t is the predicted exploitable biomass in month t.

2.8.2 Model assumptions

The main assumptions of the delay difference model were:

- Growth in mean body weight at age is described by a linear equation
- All animals aged r and older are equally vulnerable to fishing, implying knife-edged selectivity at age r.

- All animals aged r and older have the same annual natural mortality rate.
- All animals aged r and older have the same catchability.
- catch rates were proportional to abundance,
- age at first recruitment to the fishery and age at maturity were both equal to four months, and
- mean growth function for prawn weight was over both sexes combined

2.8.3 Model parameters

Table 2.3 Fishery Constants and Biological parameters used in the delay difference model

Parameter	Value	fixed/estimated	Description
Fishery Constants			
start year	1941	fixed	commencement of the fishery
end year	2019	fixed	final year of data
recfishyr	32	fixed	number of years of recruitment deviations (2019 −1988)
rec_fyr	1988	fixed	First year to estimate recruitment deviations
Biological Parameters			
Natural Mortality			
M	0.18	fixed	One parameter for instantaneous natural mortality per month
Recruitment			
R_{init}	1.65	estimated	Used to determine R_0 (Equation 2.11)
R_0 scaler	10^8	fixed	scaler for R_0
ζ	mean $= 0$, sd $= 0.1$	estimated	recruitment deviates, normal random, for n recruitment years (see recfishyr)
μ	0.5	estimated	Mode of the monthly recruitment pattern
κ	1.5	estimated	Concentration of the monthly recruitment pattern
Stock Recruitment			
ξ	$\log(3)$	estimated	Used to determine Beverton-Holt steepness h (Equation 2.13)
Brody growth coefficient			
ρ	0.934	fixed	*P. esculentus* 0.935 (female) 0.949 (male) *P. semisulcatus* 0.95 (female) 0.902 (male) monthly growth
Length to weight			
alpha	0.0026	fixed	Average weight (g) at length l (divide by 1000 for kg)
beta	2.67	fixed	(see Equation 2.9)
Weight at recruitment into model			
wt rec	0.010 0.003	fixed	weight at recruitment and at one month prior (kg)
Other parameters			
nllp	0 (0.005)	fixed	Standard deviation for any -LL penalties
sigRlow	0 (0.1)	fixed	Lower bound on annual recruitment
sigRup	0 (0.2)	fixed	Upper bound on annual recruitment
sigma2	0 (0.06)	fixed	minimum log catch rate stddev for nll; for post-1987 logbook data

2.8.4 Matching predictions to data

The model was optimised by fitting the predicted catch rates to a time series of monthly standardised catch rates by adjusting the estimated parameters (see Table 2.3). Whole-of-fishery standardised time series of catch rates were tuned as abundance indices assuming a lognormal distribution. Predicted fishery catch rates were adjusted to mid-month values. Monthly exploitable biomass was taken as the biomass at the end of the month after 100% of fishing and natural mortality had occurred.

Monthly catch rates: fishery

The predicted monthly catch rates were estimated according to Equation 2.19

$$c_t = q_t B_t \tag{2.19}$$

where c_t was the monthly catch rate (kg boat-day^{-1}) q is a closed form of the catchability coefficients calculated as an average (Haddon 2011), B is exploitable biomass, and ϵ are the recruitment deviates.

The likelihood function (specifically the negative log likelihood) was used to minimise an objective function of observed catch rate data according to Haddon (Haddon 2011).

$$-LL = \frac{n}{2}[\ln(2\pi) + 2\ln(\sigma) + 1] \tag{2.20}$$

where $-LL$ is the negative log likelihood, n is the number of observations (restricted to the number of months were catch rate was non-zero) and σ is the the standard deviation (the square root of the variance, (Equation 2.21)

$$\sigma^2 = \frac{\sum(x - \hat{x})^2}{n} \tag{2.21}$$

where σ^2 is the variance, x is the natural log of the observed catch rate and $\hat{x}$ is the natural log of the predicted catch rate.

Two negative log-likelihoods were summed with equal weight into a single objective function: 1. commercial catch rates and 2. recruitment deviates.

The fitting procedure incorporated penalty functions to put bounds on estimated parameters and preventing the model from becoming biologically unrealistic. As mentioned a penalty function was applied to the ξ parameter to prevent unrealistically high level of steepness and hence biomass. Three penalty functions were included:

- to prevent the exploitable biomass from becoming lower than the catch
- to prevent the number of recruits in each month being lower than the number of prawns in the observed catch
- to prevent unrealistically large steepness (greater than 0.5)

2.8.5 Model uncertainty

The fitting procedure used maximum likelihood estimation (using the ‘optim’ followed by the ‘nlm’ functions in R, (R Core Team 2020)). The best fitting parameter estimates and their covariance matrix were stored for estimating uncertainties in biomass. Uncertainty in parameter estimates was based on asymptotic errors using a variance-covariance matrix. A new vector of parameters was generated using the best fitting estimates as the mean and the asymptomatic errors as the variation around the mean. Confidence intervals on all outputs (e.g. biomass and catch rate) were generated by a Monte Carlo routine of generating 2000 variations in the parameters vector and running each vector through the models (Haddon 2020). The following algorithms were used to generate 95% confidence intervals:

1. Use the estimated model parameters and the covariance matrix of their estimators to construct a multivariate normal distribution.
2. Draw a random sample parameter vectors from the multivariate normal distribution.
3. Assumed known parameters were fixed.
4. Use the random sample of parameters to obtain a sample historical trajectory for the stock (i.e. run model with the sampled parameter vector).
5. Repeat the process from step two to four 2000 times to obtain 2000 trajectories and outputs, each of which reflects the correlations among parameter estimates.
6. Calculate 2.5% and 97.5% percentiles to generate 95% confidence intervals.

3 Results

3.1 Model inputs

3.1.1 Harvest estimates

Tiger prawn catch data for the northern and central regions show that most of the catch occurred in the north (Figure 3.1). Harvests in the north decreased in 2007 from the high levels observed since 1988 and are sporadic in the central region (with fluctuations). The sporadic catches in the central region may indicate that the fishery is not always targeting tiger prawn and instead is responding to levels of catches of other species, possibly targeting Moreton bay bug and redspot prawn, or levels of catches elsewhere.

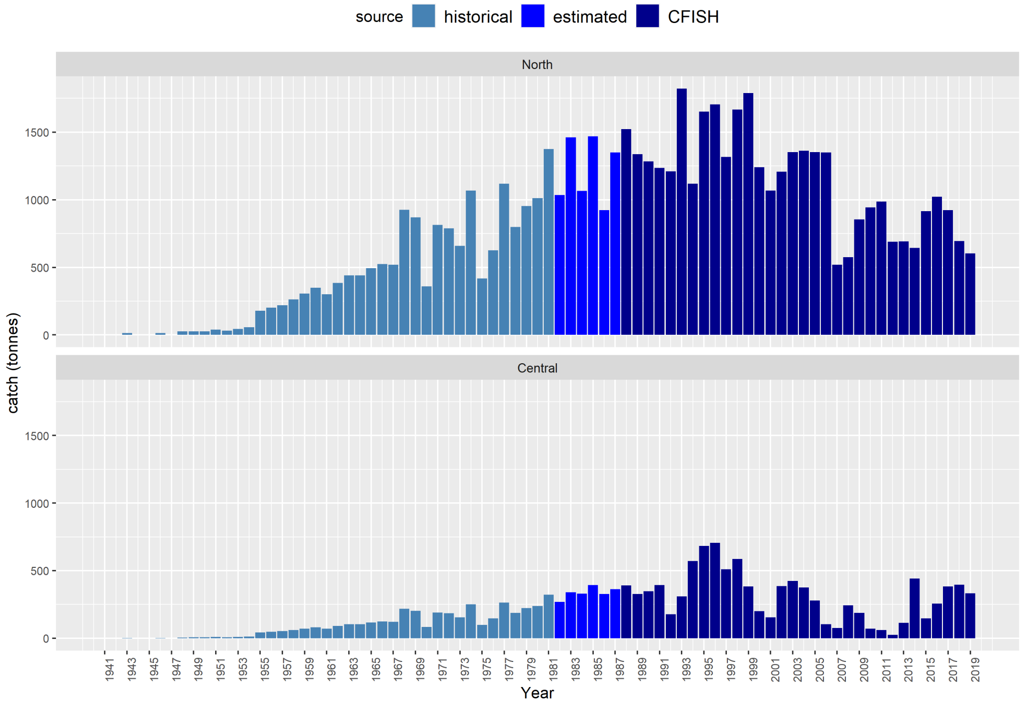


Figure 3.1 Total annual derived and reported landed catch of tiger prawns from 1941 to 2019 for the northern and central regions

3.1.2 Fishing power

Fishing power gradually increased in the central region from 1989 to 2020 while remaining relatively stable in the northern region (18% increase in the central region, approx 0% northern region, Figure 3.2). The increase in fishing power highlighted the need to take fishing power into account when reporting long-term trends in catch rates, and assessing the stock. The increase in fishing power may still be an underestimate because horsepower used in the assessment is based on the values on the licences which may be lower than those recorded in the fishers logbooks.

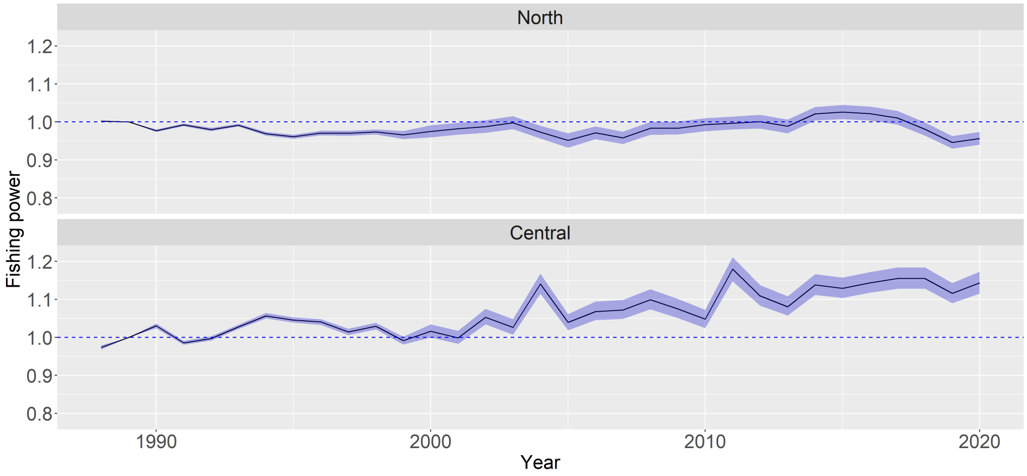


Figure 3.2 Fishing power for the tiger prawns in the northern region and central region from 1988 to 2020 with 95% confidence intervals. Fishing power is relative to 1989 levels (blue dotted horizontal line)

Increases in fishing power were mostly driven by the presence of vessels with more efficient gears being more active in the fishery (i.e. changing fleet profile expressed by the random term). The following gear and vessel characteristics resulted in increased in fishing power: higher engine rated power, speed, the use of ground gear, net type and propeller nozzle.

3.1.3 Abundance indices

3.1.3.1 Commercial standardised catch rates

Catch rates were standardised to represent trends in the abundance of tiger prawns taking into account fishing power (Figure 3.3). Monthly catch rates were used as a model input but for characterising the trend of the timeseries annual catch rates are use. Annual catch rates have steadily increased since 1988 in the northern region and only slightly in the central region, with the north having higher catch rate than the central region. There was a notable increase in the standardised catch rates in the north between 2000 and 2006 with a decline in 2007 before increasing again from 2008–2010, and have since stabilised. In the central area there have been regular fluctuations since 2000, with short spikes (one–two years) followed by decreases. A similar pattern was observed in catches. The sporadic catch rates in the central area may indicate that the fishery is not always targeting tiger prawn and instead is responding to levels of catches of other species or levels of catches elsewhere.

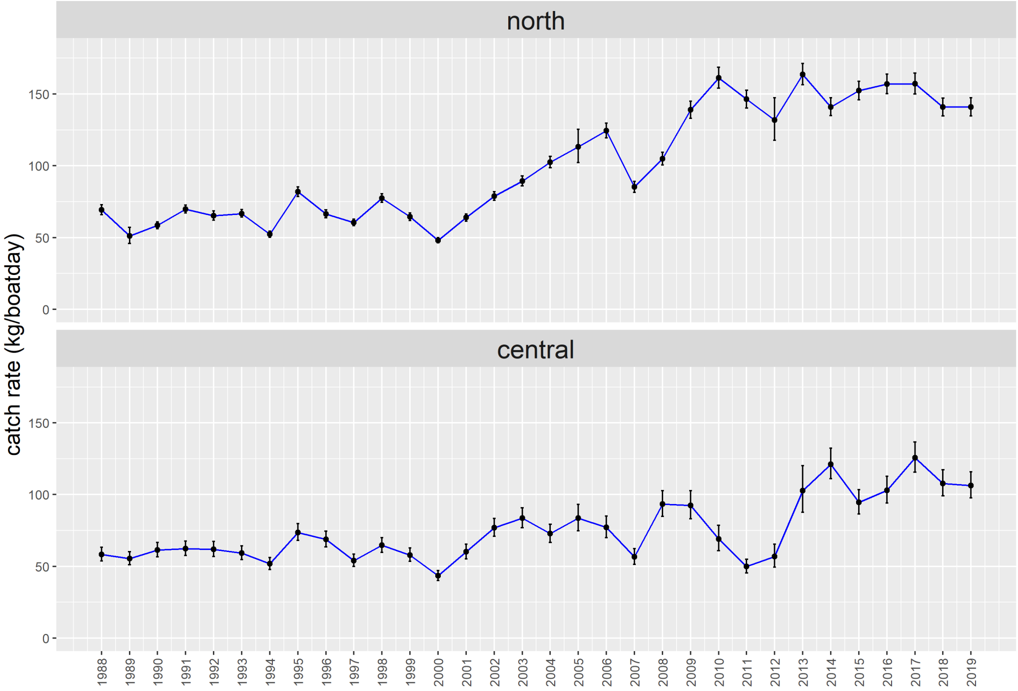


Figure 3.3 Annual standardised catch rates (with 95 % confidence intervals) for tiger prawns in the northern and central regions from 1988 to 2019

3.2 Model outputs

Results from the model outputs are informed by input data for monthly harvests, catch rates and by fixed model parameters (Table 2.3).

3.2.1 Model parameters

In total there were 34 parameters estimated by the model including 30 for annual recruitment, one for initial recruitment (R_{init}), two for monthly pattern in recruitment (κ and μ) and one for transformed steepness of the Beverton-Holt equation (ξ). The fitted parameter values are presented (excluding the 30 annual recruitments) as a table of median values and confidence intervals after the fitting procedure resulting from the hessian (Table 3.1).

Table 3.1 Estimated model parameters with upper and lower confidence intervals — estimated recruitment deviates from the 30 annual recruitment estimates are not presented

Parameter	Description	Median	2.5%	97.5%
R_{init}	initial recruitment	0.4985	0.4931	0.5041
κ	Concentration of the monthly recruitment pattern	1.33	1.16	1.50
μ	Mode of the monthly recruitment pattern	2.88	2.77	3.00
ξ	Used to determine Beverton-Holt steepness h (Equation 2.13)	0.6931	0.6926	0.6934

3.2.2 Model fits

The model was fitted to commercial standardised catch rates for the northern and central regions (Figure 3.4). The breaks in the time series refer to seasonal closures in January and February since year

2000. The predicted catch rate did not fit the high extremes well and had fitted the lower end of the values more often. This fitting behaviour was consistent throughout the majority of timeseries.

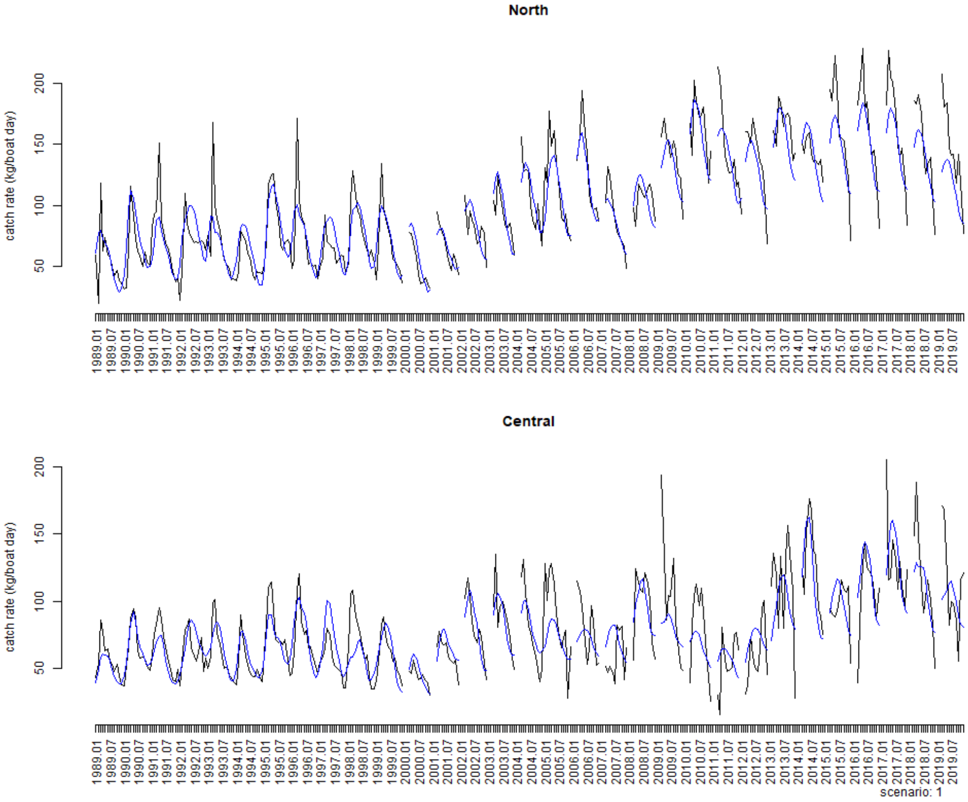


Figure 3.4 Observed (black) and predicted (blue) standardised catch rates.

3.2.3 Biomass

The model estimated historical exploitable biomass, expressed as a median ratio of biomass relative to 1941. The biomass declined to roughly 20% in 1990 and although it has fluctuated since then, it increased to 49% in northern region and 50% in central region in 2019 (Figure 3.5).

Figure 3.5 Annual exploitable biomass and 95% confidence intervals

3.2.4 Harvest targets

Current harvests, fishing efforts and reference points are detailed in Table 3.2. The relevant harvest strategies are the Trawl (Northern Region) Harvest Strategy and the Trawl (Central Region) Harvest Strategy. The harvest strategies state that the target reference point for biomass is 60% and the limit reference point for biomass is 20% (Department of Agriculture and Fisheries 2020b; Department of Agriculture and Fisheries 2020a). The key population performance indicator was an annual estimate of biomass. The annual estimate of maximum sustainable yield (MSY) was 1216 tonnes in the northern region and 311 tonnes in the central region. The 2019 harvest was 602 tonnes in the northern region and 333 tonnes in the central region. Effort levels were estimated from the standardised catch rate and in the case of reference points from fitted catch rate generated from the model (Appendix C.3). The 2019 effort (standardised) was 3874 boat-days/year in the northern area and 2986 boat-days/year in the central area.

Table 3.2 Current and target indicators—target reference point for biomass (exploitable biomass) ratio is 60%

Parameter	**Estimate**
Northern Region	
Exploitable biomass ratio in 2019 (B_{2019}/B_{1941})	49%
Exploitable biomass ratio at MSY	34%
2019 harvest	602 tonnes
Maximum sustainable yield (MSY)	1216 tonnes
Maximum yield at B_{targ}	978 tonnes
Fishing effort in 2019: standardised	3874 boat-days
Fishing effort in B_{2019} (E_{2019} for mean 2015–2019 fishing power)	3824 boat-days
Fishing effort for B_{MSY} (E_{MSY} for mean 2015–2019 fishing power)	10 911 boat-days
Fishing effort for B_{targ} (E_{targ} for mean 2015–2019 fishing power)	5235 boat-days
Central Region	
Exploitable biomass ratio in 2019 (B_{2019}/S_{1941})	50%
Exploitable biomass ratio at MSY	36%
2019 harvest	333 tonnes
Maximum sustainable yield (MSY)	311 tonnes
Maximum yield at B_{targ}	252 tonnes
Fishing effort in 2019: standardised	2986 boat-days
Fishing effort in B_{2019} (E_{2019} for mean 2015–2019 fishing power)	1276 boat-days
Fishing effort for B_{MSY} (E_{MSY} for mean 2015–2019 fishing power)	3443 boat-days
Fishing effort for B_{targ} (E_{targ} for mean 2015–2019 fishing power)	1686 boat-days

4 Discussion

4.1 Stock status

Biomass as estimated by the model was 49% in 2019 in the northern region, and 50% in the central region, both below the target reference point of 60%. Biomass estimates are based on exploitable biomass because the model generates biomass at age four+ months, however maturity is six months. It is possible to refer to exploitable biomass as spawning biomass only if the age of recruitment is close to the age at maturity (Dichmont et al. 2003).

It is uncertain if the stock would rebuild to the target biomass ratio of 60% under current harvest conditions given that the biomass trajectory indicates a decline in the last two years. The decline in biomass was likely a combination of environmental conditions (Vance et al. 1985) and previous years effort that was only just starting to have an effect. It is to be noted that historically the fishery harvested juveniles. However to protect the juvenile portion, seasonal closures were introduced in 2000 and no trawling was allowed in January and February.

In an effort managed fishery, effort levels are adjusted in order to achieve target biomass. The level of adjustment depends on how quickly the stock needs to rebuild. Currently the requirement of the harvest strategy is to achieve maximum economic yield or 60% biomass by 2027 (Department of Agriculture and Fisheries 2017). Currently biomass is below the target but within the goal of the current harvest strategy which is to achieve 40–50% biomass by 2020. The stock needs to improve from its current biomass to achieve the target by 2027. To improve the stock biomass and achieve target, effort levels need to be 3824 boat days/year in the northern region and 1276 boat days/year in the central region. Effort is currently 3874 boat days/year, which is slightly above 3824 boat days/year, and therefore effort needs to be reduced. In the central region effort needs to be 1276 boat days/year to achieve target. Effort is currently 2986 boat days/year, which is higher that 1276 boat days/year, and therefore the biomass in the central region is unlikely to improve if effort remains at current level. To determine the time taken to achieve 60% target, will require projection of future biomass trajectories to determine the level of annual catch and effort that that would allow the the stock biomass to reach target levels.

Analysis of standardised residuals indicated that the delay difference model fitted the data appropriately and that the assumed error structures were valid. No concerning correlations of key parameter estimators were evident.

The model predicted the standardised catch rates sufficiently well, although it fitted better to the lower monthly values than the higher monthly values. The predicted estimates were consistent with the observed estimates in the years where there were not high extremes but did not fit to the extreme levels which were more common in the last five years of the time series. In this period the predicted catch rate was within the range but more contracted. When considering the biomass ratio in the context of the fit in catch rate, it is the trend of the fitting behaviour that is important. Particularly if there is a need to estimate current biomass ratio relative to the starting point (when fishing began in 1941). Provided that the fitting behaviour is the same (or biased equally) throughout the time series the biomass trend might be the same whether the entire time series was consistently fitted to high values or consistently to low values. Problems arise when the fitting behaviour changes differentially over the recent years as this unequal bias would affect the relative biomass trend differentially. Overall the fitting behaviour was relatively consistent throughout the time series and might not have affected the resulting biomass trend deferentially. The high extremes in the catch rates can be suggestive of some of the limitations of the method including the catch rate standardisation. In a similar catch rate standardisation for tiger prawns in the Torres Strait fishery, the standardised catch rate did not exhibit high extremes compared to the nominal catch rates (Turnbull 2019).

It is possible that the catch rate is hyperstable if tiger prawns aggregate in schools. The risk of this might have been reduced by accounting for fishing power.

One of the key features underlying this assessment is the careful selection of reference levels when estimating catch rate and fishing power. REML was used in the linear modelling and reference levels for vessel was explicitly identified. The selection of the 'reference' vessel is considered to improve the stability of the catch rate indices and fishing power estimates.

The stock dynamics during the period 1941 to 1987 are informed (or extrapolated) from the model fitted to data available between 1988 to 2019 (the time series of standardised catch rates). In addition there are a number of key assumptions. Growth rates and natural mortality were assumed to be constant throughout the period. Other key assumptions are related to the recruitment aspects of stock dynamics and include:

- the assumption that the use of the concept of an R_0 (and its equivalent B_0 - unfished biomass) is valid with an opportunist species such as a tiger prawn (which is effectively annual in its dynamics, Equations 2.11 to 2.15)
- the assumption that the stock was in an equilibrium, unfished state in 1941 (from Figure 3.5)
- the assumption that the Beverton-Holt stock recruitment relationship (with associated recruitment residual structure) provided an acceptable description of recruitment dynamics. That is, the equations were capable of capturing the biological recruitment dynamics as well as variations introduced by environmental factors, which in every other tiger prawn fishery are known to be very influential.

4.2 Fishing power

Although there was no detectable increase in fishing power in the northern region, the 18% increase in fishing power in the central region was consistent with previous reports: approximately 18% over 25 years from 1988 to 2013 (Wang 2015). The number of boats accessing the fishery has remained stable in Queensland since 2012.

4.3 Recommendations

4.3.1 Monitoring

Updating the length-to-weight conversion formula by collecting length and weight data will improve the robustness of the model.

Since the last biological survey 10 years ago, three generations of prawn populations have elapsed, and temperature may affect the population biology of marine ectotherms. An updated collection of biological data such as growth and maturity is required.

If the fishery management objectives include economic targets, such as MEY and E_{MEY} reference points, then collection of economic data is required.

4.3.2 Management

To build the stocks to the 60% biomass ratio target reference point, considerations for management are as follows:

- The recommended effort in the northern region should currently be reduced from 3874 boat days to 3824 boat days.
- In the central region, the recommended effort should be reduced from 2986 boat days to 1276 boat days.

4.3.3 Assessment

Future analyses could consider including a longer time series of catch rates once an agreed method has been developed.

The effect of fishing power might have been underestimated. It is recommended that

- that the same data filters be applied to the gear and vessel data that were applied to the catch rate data. Specifically, that the data be filtered to included only the grids and vessels that were used in the catch rate analysis (as was done for the estimation of fishing power for eastern king prawns).
- once the gear and vessel data are filtered that forward filling of values be carried out where there are missing values were also filled. The premise is that gear and vessel characteristic are unlikely to change from one day to another for a given vessel within a proximal time period (within reason). Therefore if entries for certain gear or vessel characteristics are missing within a particular vessel it is reasonable to assume that the same values will apply as what was in the previous record for that vessel.
- the reporting of horsepower be used rather than the values in the database not being an accurate reflection of reality.

It is possible that historical catches are slightly overestimated and this will have had the effect of increasing the B_{MSY} and B_{targ}.

The current assessment used a constant annual catchability. It is recommended that future assessment use monthly catchability. This is because prawns might be easier to catch in some months than others. When prawns recruit into the fishery at a given month they are easier to catch. As the year progresses the number of prawns become depleted and individuals grow bigger making it harder to catch in those months.

In the current assessment the harvest rate rate was constrained to be above 20% of the exploitable biomass and therefore the model would have adjusted the biomass to satisfy this constraint. It is recommended to explore and evaluate different constraints.

For future assessments, it is recommended to use horsepower that is recorded in the logbook data.

Given the possibility of uncertainty in the current R_{init}, it is recommended other values be considered and a likelihood profile be generated to determine whether the model fit improves.

4.4 Conclusions

The tiger prawn fishery is a commercially valuable stock in Queensland. This assessment has informed the status of the tiger prawn population in the northern region and central region of the East Coast Otter

Trawl Fishery. The results provide empirical performance measures (catch rates) against model based performance indicators (B_{MSY}, E_{MSY}).

To build the stocks to the 60% biomass ratio target reference point, effort in the northern region should be slightly reduced from 3874 boat days to 3824 boat days. In the central region, effort should be reduced from 2986 boat days to 1276 boat days: being below half the current level.

References

Australian Bureau of Agricultural and Resource Economics and Sciences (2018). *Australian fisheries and aquaculture statistics 2018 - Production*. URL: `https://www.agriculture.gov.au/abares/research-topics/fisheries/fisheries-data#australian-fisheries-and-aquaculture-statistics-2018`.

Beverton, Raymond J. H. and Sidney J. Holt (1957). *On the Dynamics of Exploited Fish Populations*. London: Chapman and Hall.

Courtney, AJ, MF O'Neill, M Braccini, George M Leigh, M Kienzle, Sean Pascoe, AJ Prosser, You-Gan Wang, L Lloyd-Jones, AB Campbell, et al. (2014). *Biological and economic management strategy evaluations of the eastern king prawn fishery*. Tech. rep.

Department of Agriculture and Fisheries (2017). *Queensland Sustainable Fisheries Strategy 2017–2027*. Tech. rep. Brisbane: Queensland Department of Agriculture and Fisheries. URL: `https://www.daf.qld.gov.au/business-priorities/fisheries/sustainable/sustainable-fisheries-strategy/sustainable-fisheries-strategy-overview`.

— (2020a). *Trawl fishery (central Region) harvest strategy: 2021 –2026: CONSULTATION DRAFT*. Tech. rep. Brisbane: Queensland Department of Agriculture and Fisheries. URL: `https://daf.engagementhub.com.au/draft-trawl-harvest-strategies`.

— (2020b). *Trawl fishery (Northern Region) harvest strategy: 2021 –2026: CONSULTATION DRAFT*. Tech. rep. Brisbane: Queensland Department of Agriculture and Fisheries. URL: `https://daf.engagementhub.com.au/draft-trawl-harvest-strategies`.

Deriso, R. B. (1980). "Harvesting Strategies and Parameter Estimation for an Age-Structured Model". In: *Canadian Journal of Fisheries and Aquatic Sciences* 37.2, pp. 268–282. URL: `http://www.nrcresearchpress.com/doi/abs/10.1139/f80-034`.

Dichmont, CM, AE Punt, A Deng, Q Dell, and W Venables (2003). "Application of a weekly delay-difference model to commercial catch and effort data for tiger prawns in Australia's Northern Prawn Fishery". In: *Fisheries Research* 65.1-3, pp. 335–350.

Haddon, Malcolm (2011). *Modelling and Quantitative Methods in Fisheries*. 2nd. Boca Raton, FL: CRC Press.

— (2020). *Using R for Modelling and Quantitative Methods in Fisheries*. Boca Raton, FL: CRC Press.

Hilborn, Ray and Carl J. Walters (1992). *Quantitative Fisheries Stock Assessment: Choice, Dynamics & Uncertainty*. Dordrecht, Netherlands: Kluwer.

Mardia, Kanti V and Peter E Jupp (2009). *Directional statistics*. Vol. 494. John Wiley & Sons.

O'Neill, Michael F and Clive Turnbull (2005). *Stock assessment of the Torres Strait tiger prawn fishery (*Penaeus esculentus*)*. Department of Primary Industries and Fisheries.

O'Neill, Michael F, Anthony J Courtney, Clive T Turnbull, Norm M Good, Kate M Yeomans, Jonathan Staunton Smith, and Celeste Shootingstar (2003). "Comparison of relative fishing power between different sectors of the Queensland trawl fishery, Australia". In: *Fisheries Research* 65.1-3, pp. 309–321.

R Core Team (2020). *R: A language and environment for statistical computing*. Vienna. URL: `http://www.R-project.org/`.

Turnbull, Clive (2019). *Updated tiger prawn stock assessment for the Torres Strait prawn fishery. A Final Report to AFMA for the TSPMAC and TSSAC. Project: 180802*. Tech. rep., pp. 1–16.

Turnbull, Clive T and Joanne C. Atfield (2007). *Fisheries long term monitoring program: summary of tiger and endeavour prawn survey results: 1998-2006*. Tech. rep. Brisbane, Australia: Department of Primary Industries and Fisheries.

Vance, DJ, DJ Staples, and JD Kerr (1985). "Factors affecting year-to-year variation in the catch of banana prawns (Penaeus merguiensis) in the Gulf of Carpentaria, Australia". In: *ICES journal of marine science* 42.1, pp. 83–97.

VSN International (2019). *Genstat for* Windows *20th Edition*. Type: Computer Program. VSN International, Hemel Hempstead, UK. URL: `Genstat.co.uk`.

Wang, Na (2015). "Sustainability and optimality in fisheries management". PhD thesis.

Ward, Robert D, Jennifer R Ovenden, Jennifer RS Meadows, Peter M Grewe, and Sigrid A Lehnert (2006). "Population genetic structure of the brown tiger prawn (*Penaeus esculentus*) in tropical northern Australia". In: *Marine Biology* 148.3, pp. 599–607.

A Data sources

Table A.1 shows a description of data sources used and procedures applied to prepare the data.

Table A.1 Data procedures used to define the fishery data that was included in the analysis of catch effort, gear trends and fishing power

Data	Details	Notes
Queensland		
CFISH data extraction	Data extracted 1/8/2020; SQL script held by Assessment and Monitoring	
	Fisheries Policy and Sustainability, Fisheries; Primary Industries Building Brisbane	Catches, effort, Year, month, start Date, end Date, Vessel ID, licence ID, Gear, depth, sector / spatial location, length, grading. request: all prawns
Time period	02/01/1988 to 28/10/2019	
Data sets	Separate tables were provided for commercial prawn catch-effort, commercial boat info, and boat gear	
Daily records	Only daily records were analysed and were identified by the same operation date and end date of fishing.	Data were grouped by Authority Chain Number and operation date to make daily (harvests > 0 for each species group).

B Model inputs

B.1 Harvest

The total catch for each of the two regions in the Queensland East Coast Otter Trawl Fishery considered in the current assessment is provided in Table B.1.

Table B.1 Total catch (tonnes) used in the analyses of the Queensland tiger prawn fishery in the northern and central regions

Year	North	Central	Year	North	Central	Year	North	Central
1941	0.1	0	1968	924.5	216.8	1995	1652.7	682.3
1942	0.2	0	1969	870.1	204	1996	1706.1	705.8
1943	12.5	2.9	1970	359.4	84.3	1997	1316.7	510.4
1944	0.5	0.1	1971	813.7	190.8	1998	1666.3	585.8
1945	0.7	0.2	1972	789.5	185.1	1999	1789	384
1946	12.9	3	1973	659.4	154.6	2000	1239.6	199.5
1947	1	0.2	1974	1068.2	250.5	2001	1068.3	155.7
1948	25.3	5.9	1975	417.3	97.9	2002	1207.4	385.4
1949	25.5	6	1976	626.3	146.9	2003	1351.8	424.8
1950	25.6	6	1977	1119.9	262.6	2004	1362.1	375.3
1951	37.9	8.9	1978	799.1	187.4	2005	1352.7	279.6
1952	32	7.5	1979	953.5	223.6	2006	1349.6	103.6
1953	44.2	10.4	1980	1011.1	237.1	2007	519.3	74.6
1954	56.5	13.2	1981	1374.5	322.3	2008	576	243.8
1955	177.7	41.7	1982	1062.6	430.3	2009	854.5	186.5
1956	202.1	47.4	1983	1268.8	384.7	2010	944.2	70.7
1957	220.4	51.7	1984	893.3	277.4	2011	987.5	61.2
1958	263	61.7	1985	1359	243.8	2012	688.6	25.5
1959	305.5	71.6	1986	1046.3	218	2013	692.1	114.9
1960	348	81.6	1987	1204.5	292.1	2014	643.3	441.9
1961	299.7	70.3	1988	1523.3	389.8	2015	916.5	146.4
1962	384.7	90.2	1989	1337.9	328.5	2016	1023.3	256
1963	439.3	103	1990	1284.5	347.7	2017	922	382
1964	439.5	103	1991	1235.6	392.7	2018	693.7	395.7
1965	494.1	115.9	1992	1209.7	176.5	2019	602.4	332.7
1966	524.5	123	1993	1822.1	308.2			
1967	518.6	121.6	1994	1117.4	571.5			

B.2 Other inputs

Values for the monthly spawning pattern was the same as those reported in (O'Neill et al. 2005)

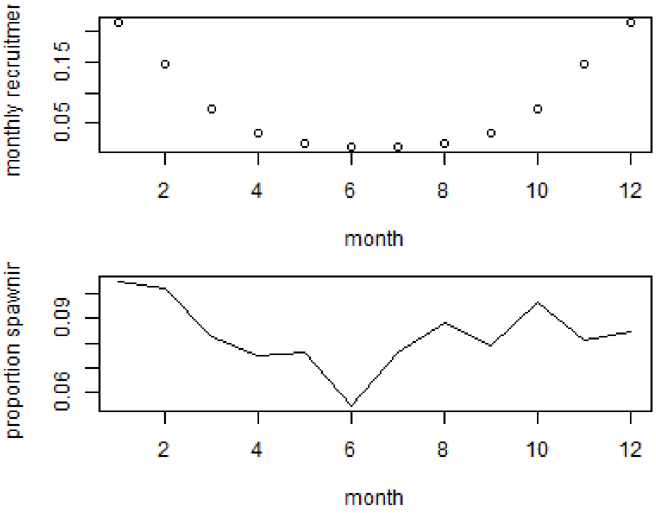


Figure B.1 Monthly recruitment and spawning pattern

Table B.2 Monthly values for recruitment and spawning pattern in tiger prawns

Month	recruitment pattern	spawning pattern
1	0.21550	0.10550
2	0.14616	0.10220
3	0.07461	0.08230
4	0.03432	0.07460
5	0.01752	0.07640
6	0.01188	0.05430
7	0.01188	0.07600
8	0.01752	0.08800
9	0.03432	0.07890
10	0.07461	0.09650
11	0.14616	0.08080
12	0.21550	0.08470

C Model outputs

C.1 Stock recruitment

Annual recruitment into the model was a function of exploitable biomass (instead of the proper spawning biomass) and followed the stock recruitment relationship as described by the Beverton-Holt model, with error.

The model predicted a gradually declining recruitment pattern prior to the year 1988 and thereafter strong fluctuations were evident coinciding with the start year (1988) of recruitment estimates in the model (Figure C.1,Figure C.2). Results from fishery independent surveys between 1998–2006 indicate that in Far North Queensland recruitment was above average in 1999 and 2005 and below average in 2000 (Turnbull et al. 2007). Assessment results from the northern area (between 1998–2006) are consistent with the survey results and higher than average recruitment occurred in 1998, 1999, 2004, 2005, 2006 and below average recruitment in 2000, having the lowest recruitment during the 1998–2006 period.

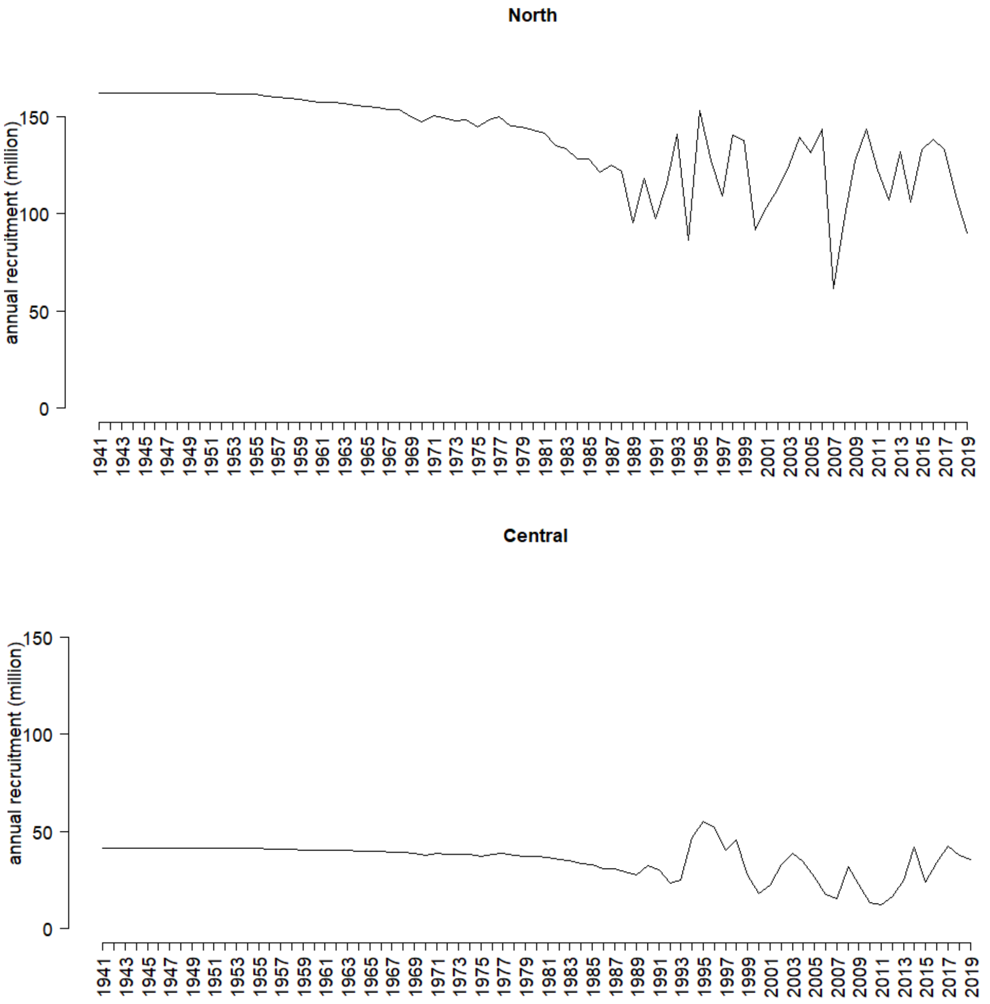


Figure C.1 Recruitment ratio estimated by the model

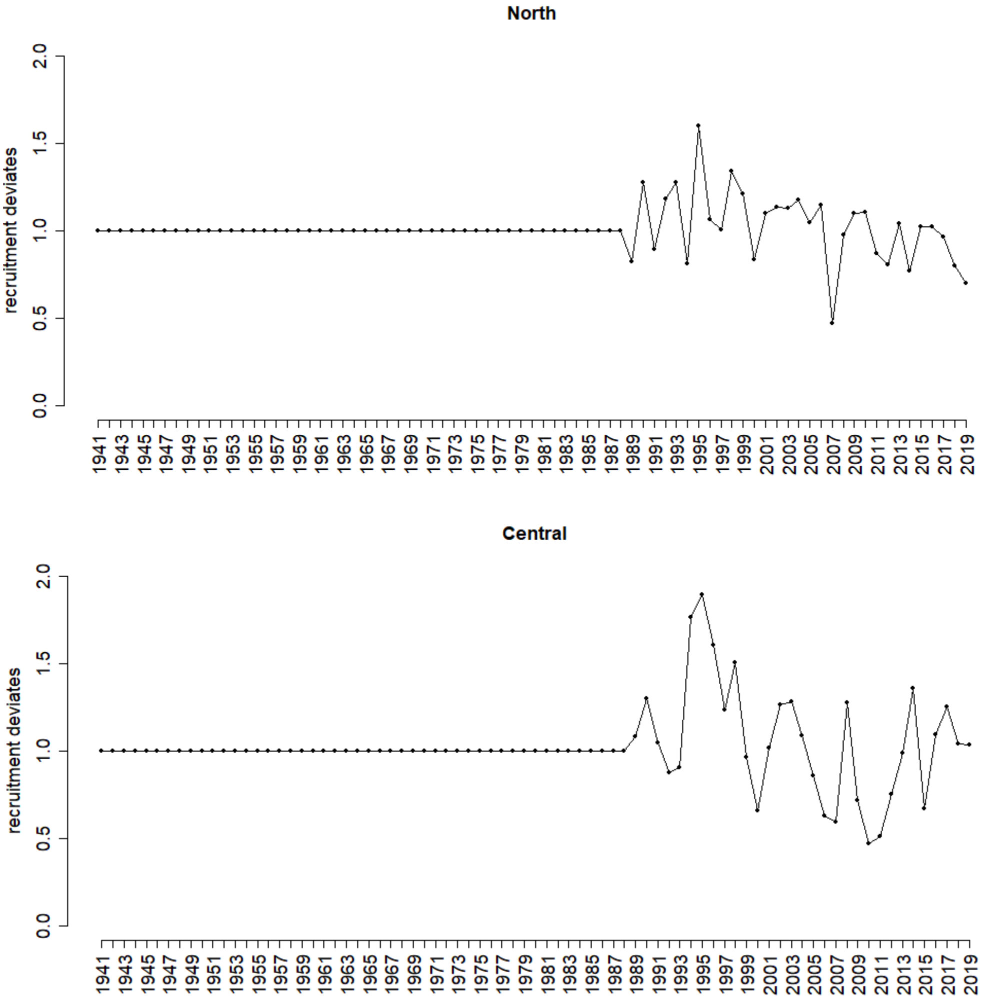
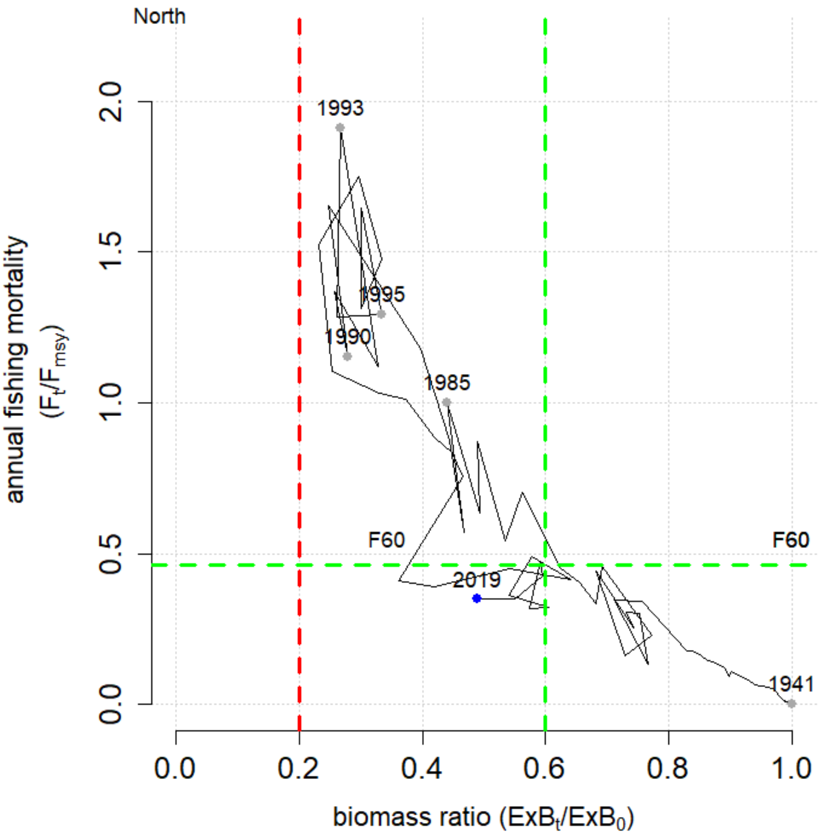


Figure C.2 Recruitment deviations estimated by the model

C.2 Phase plot

The annual condition of the stock relative to the fishing mortality for each year shows the trajectory over time of fishing mortality verses spawning biomass ratio (Figure C.3). Fisheries Queensland aims to maintain stock at a spawning biomass at 60%. The population model calculates the harvest rate (or fishing mortality) required to maintain the biomass at various levels. This harvest rate, required to maintain the stock at 60% biomass is denoted F_{60} (as shown on the phase plot).



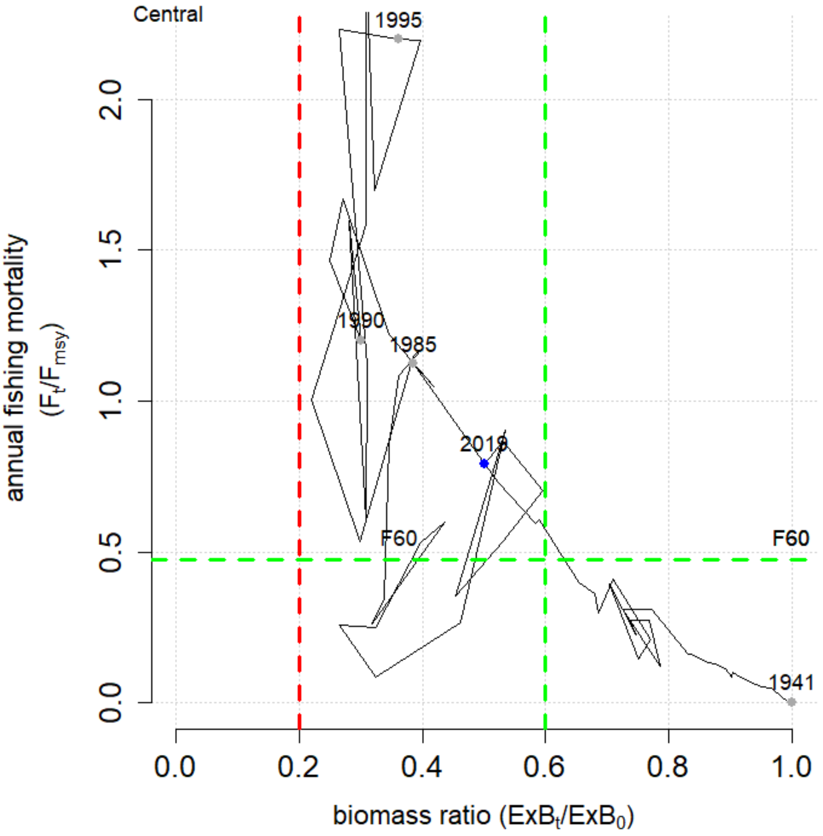


Figure C.3 Annual fishing pressure relative to the estimated biomass ratio

C.3 Calculation of reference points

The estimation of reference points was determined by running the model with the optimum parameters and generating outputs of exploitable biomass ratio, catch and effort at different levels of seasonal fishing mortality. Harvests were calculated from fishing mortality estimates ranging from 0–2, in increments of 0.001. Annual values were adjusted to monthly values in the following manner:

- estimate the monthly harvest ratio of the last five years of the timeseries (i.e. 2014–2019)
- translate the harvest rate (hr) into fishing mortality ($F = -log(1 - hr)$
- take the five year average of each month to obtain average monthly fishing mortality
- divide the monthly value by the sum of the monthly values to normalise the data. These are the monthly proportions of fishing mortality
- multiply the annual F applied in the model with the monthly proportion

MSY was determined as the level of fishing mortality that resulted in the highest level of catch under a steady state biomass ratio. In this way estimates of effort were obtained at MSY by dividing the harvest (from the model) with the catch rate (from the model). Similarly catch and effort was estimated at different levels of steady state exploitable biomass ratio including the target (B_{60}) and the limit (B_{20}) reference points. The fishing mortality associated with these different biomass ratios was also recorded.

A common question by managers in effort managed fisheries is what level of effort is required to sustain the stock at a nominated biomass ratio. It is reasonable to expect that the less depleted the stock the less effort should be expended to maintain the stock in that condition. Originally it was assumed that the relationship between effort and biomass ratio would be linear however this is not the case. Instead it is exponential (Figure C.4). This may help managers understand the connection between effort reported by the model at different biomass ratios (either B_{targ} or B_{MSY}) that are presented in the harvest targets in Table 3.2.

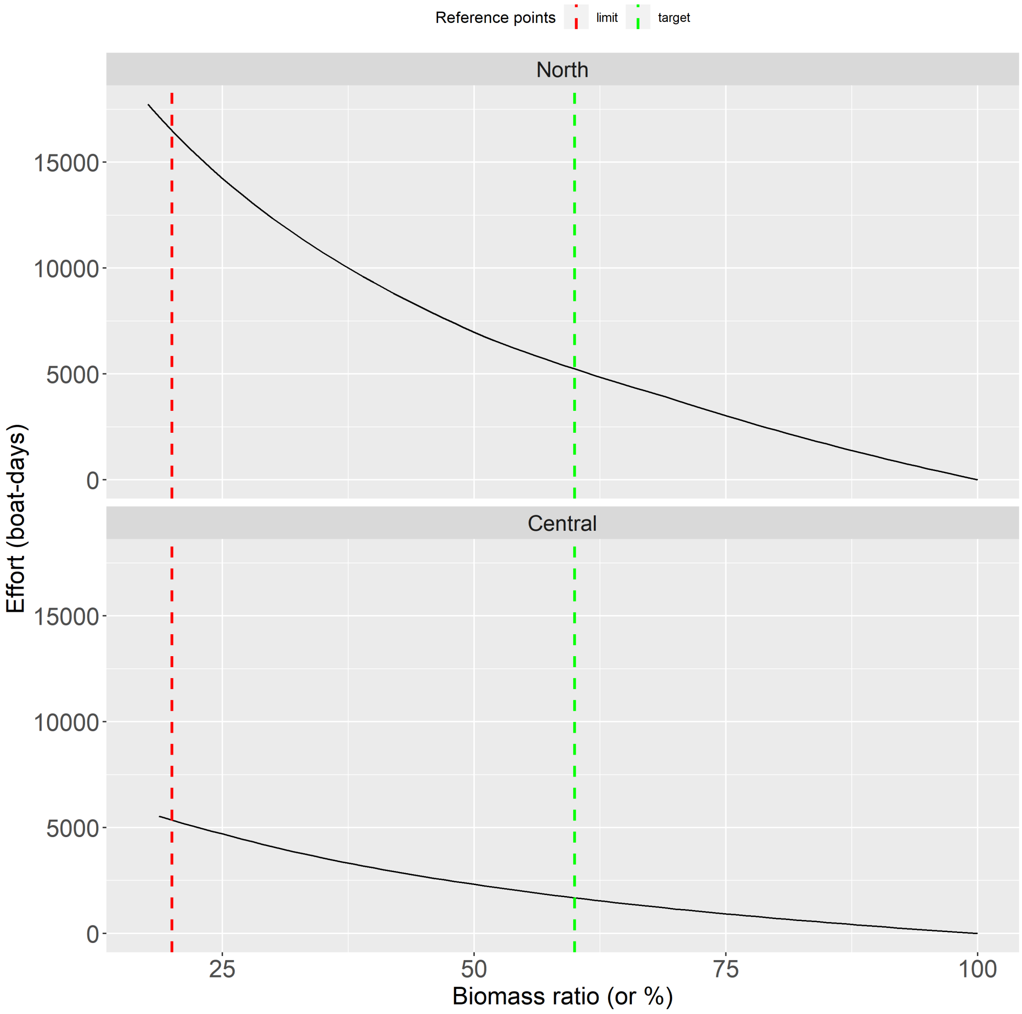


Figure C.4 Relationship between effort reported by the model at different steady state biomass ratios. The red line is the limit reference point at 20% biomass and the green line is the target reference point at 60% biomass