Stock assessment of eastern king prawn (*Melicertus plebejus*)

2020

Queensland Government

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Summary

Eastern king prawns (*Melicertus plebejus*) are endemic to Australia and are distributed on the eastern Australian coast between Hayman Island in Queensland (20° S) and north-eastern Tasmania (42° S) (Montgomery 1990). The fishery for eastern king prawns occurs mainly in New South Wales and Queensland, and predominantly caught by trawl. Genetic studies indicate that eastern king prawn is one biological stock (Chan 2015) and exhibits strong stock connectivity throughout its range (Montgomery 1990; Taylor et al. 2020). In this assessment eastern king prawn was assessed as a whole population-stock, combining New South Wales and Queensland managed waters.

A stock assessment model was used to assess the population status of eastern king prawn. This assessment is an update of the previous length-based assessment, conducted in 2010 (O'Neill et al. 2014; Courtney et al. 2014) and incorporated updated commercial catch, effort, fishery independent abundance indices, length frequency data. The assessment included catch data from 1958 to 2019.

The assessment used a length-based population dynamics model, with six spatially stratified zones across New South Wales and Queensland. The model had a monthly time step with spatial movement, growth, spawning, and mortality dynamics. The key population performance indicator was an annual estimate of egg production, representing spawning biomass (Table 1). Egg production is related to spawning biomass and henceforth the term spawning biomass will be used instead of egg production, for consistency with other assessments. Harvest data from 1958 was assumed for the modelling purposes to represent the commencement of significant fishing mortality (i.e. near virgin state of eastern king prawns). The 2019 harvest was 2738 tonnes, with 593 tonnes from New South Wales, and 2160 tonnes from Queensland (Figure 1). The average harvest for the last five years was 2800 tonnes, ranging between 2738 and 3610 tonnes which was above the maximum sustainable yield of 2423 tonnes estimated in this assessment.

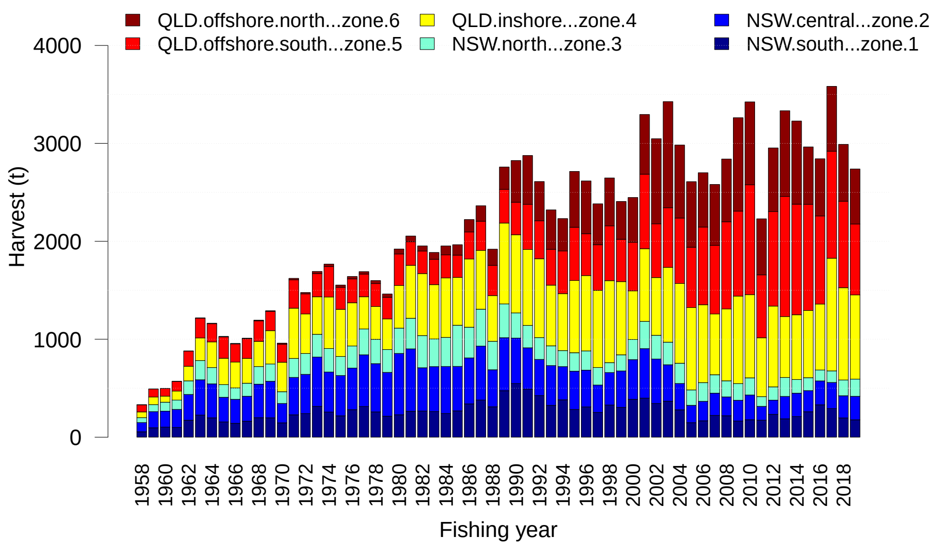

Figure 1: Annual eastern king prawn harvest in New South Wales and Queensland waters
Note: The fishing year is from 1st November through to 31st October.

Commercial catch rates were standardised and used as a model input, taking fishing power into account (Figure 2). Standardised catch rate analyses were carried out separately for New South Wales and Queensland stocks. For New South Wales the explanatory terms were year, month, zone, whiting catch and number of days fished. The unit of operation was defined to be a single month of fishing by each vessel. For Queensland the explanatory terms were year, month, zone, lunar quarter and hours fished. The unit of operation was defined to be a single day of fishing by each vessel.

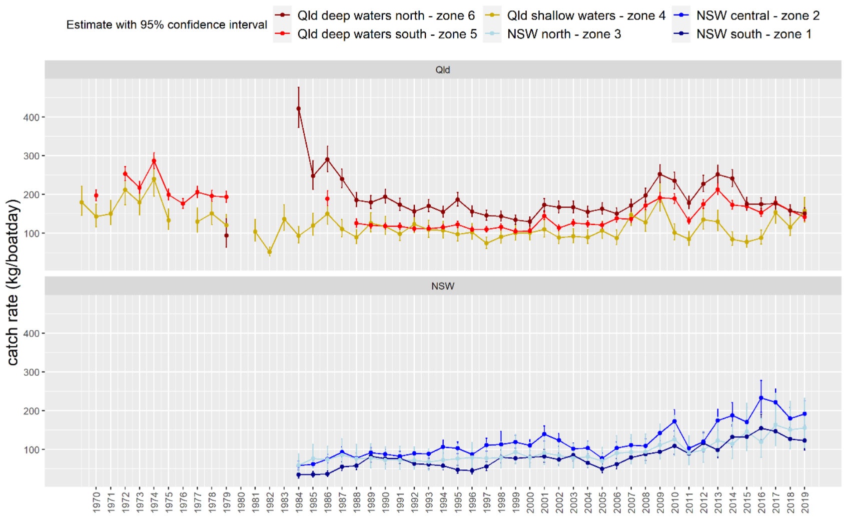

Figure 2: Annual standardised catch rates (and 95% confidence intervals) for New South Wales and Queensland eastern king prawns

The target spawning biomass S_{targ} is 60% of the unfished spawning biomass. This ensures that the fishery operates at sustainable levels, as defined in Queensland's Sustainable Fisheries Strategy 2017–2027 (Queensland 2017). The assessment estimated that the 2019 spawning biomass was 62% of the unfished 1958 level (Table 1, Figure 3). This was below the 69% biomass required for maximum economic yield but slightly above the target of 60%, suggesting that the stock is sustainable.

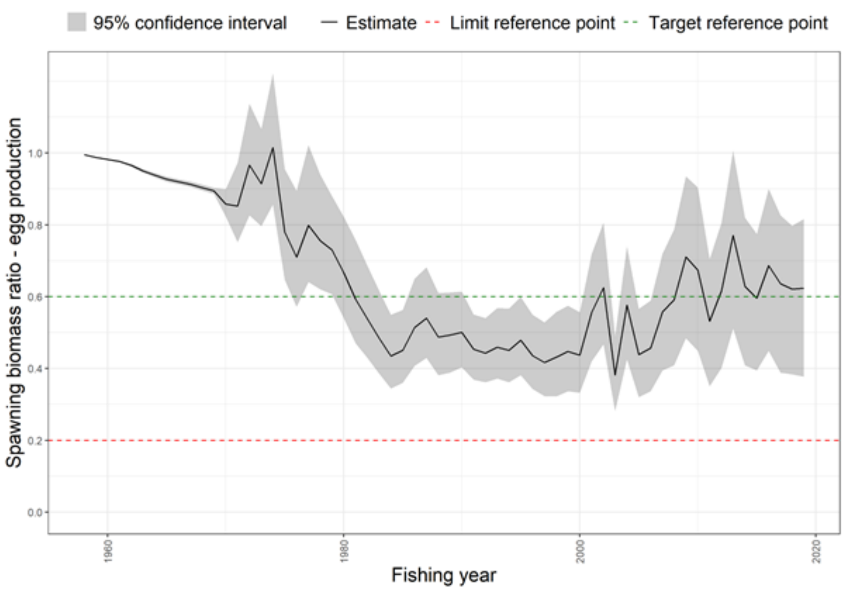

Figure 3: Annual eastern king prawn egg production relative to unfished biomass (1958) across New South Wales and Queensland waters

The current assessment estimates effort at maximum sustainable yield (E_{MSY}), standardised to the number of boat-days in 2019, to be 27 242 boat days/year. This was comparable to the previous 2010 assessment E_{MSY} of 28 300 boat days/year (Courtney et al. 2014).

Since 2010, reduced levels of fishing effort and favorable recruitment have supported harvests and catch rates of eastern king prawns. However, lower yields, reduced catch rates and reduced profits may occur if eastern king prawn recruitment falls, and fishing effort remains on average above target levels. Current management procedures and effort allocations, if fully utilised, allow for effort levels above E_{MSY}. No harvest or effort sharing arrangements or sharing caps are in place between the New South Wales and Queensland jurisdictions and these might need to be addressed in the future.

In summary, results from this assessment suggests that current harvest levels are in line with the target reference point under the Sustainable Fisheries Strategy. This study suggested the eastern king prawn fishery was sustainable and not overfished. This determination was based on the 62% spawning biomass being slightly above the target biomass of 60%.

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

Parameter	Estimate
Spawning biomass in 2019 (S_{2019}/S_{1958})	62%
Spawning biomass at MSY	42%
Spawning biomass at MEY	69%
2019 harvest from all zones	2738 tonnes
Maximum sustainable yield (MSY)	2423 tonnes
Maximum yield at S_{targ}	2155 tonnes
Maximum economic yield (MEY)	1786 tonnes
Fishing effort in 2019: standardised	15 940 boat-days
Fishing effort for S_{targ} (E_{targ})	16 450 boat-days
Fishing effort for S_{MSY} (E_{MSY} for mean 2015–2019 fishing power)	27 242 boat-days
Fishing effort for S_{targ} (E_{targ} for mean 2015–2019 fishing power)	16 450 boat-days
Fishing effort for S_{MEY} (E_{MEY} for mean 2015–2019 fishing power)	11 423 boat-days

Acknowledgements

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Glossary

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
BRD	bycatch reduction device
B_0	unfished biomass
CFISH	Queensland commercial fishery logbook database
CI	confidence interval
CL	Carapace length. Current method of measuring prawn carapace length. Unless otherwise stated it is the length from behind the eye to the back of the head i.e from the post-orbital margin to the posterior edge of the carapace.
CAAB	Code for Australian Aquatic Biota
DAFF	Department of Agriculture, Fisheries and Forestry (Queensland)
EKP	eastern king prawn
E_{MSY}	fishing effort required to achieve maximum sustainable yield
E_{MEY}	fishing effort required to achieve maximum economic yield
Fishing year	1 November to 31 October
GBRMPA	Great Barrier Reef Marine Park Authority
GPS	global positioning system
LMM	linear mixed model
MEY	maximum economic yield, including variable and fixed costs of fishing
MSY	maximum sustainable yield
S_0	unfished spawning biomass - egg production
SFS	Sustainable Fisheries Strategy (2017-2027)
S_{MSY}	spawning biomass depletion at MSY
S_{MEY}	spawning biomass depletion at MEY
S_{targ}	target reference point for spawning biomass depletion

1 Introduction

Eastern king prawns (*Melicertus plebejus*) are endemic to Australia and distributed along the eastern Australian coast between Hayman Island in Queensland (20° S) and north-eastern Tasmania (42° S) (Montgomery 1990).

Eastern king prawns (EKP) undertake northward migrations into deeper water as they grow. Spawning usually occurs in offshore areas and the East Australian Current disperses larvae southward (Everett et al. 2017). Several nursery grounds have been identified, the locations of which offer insights into the stock structure. In the northern part of the Queensland fishery, 100–170 km offshore from the central-southern Queensland coast (22–24° S), EKP utilise offshore reefs associated with the Capricorn-Bunker Islands as nursery grounds (Courtney et al. 2014). Prawns caught in the northern extent of the fishery most likely recruit from the Capricorn-Bunker Islands. In southern Queensland and northern New South Wales, EKP utilise inshore estuaries, bays and seagrass areas as nursery grounds (Courtney et al. 2014; Taylor et al. 2017).

Based on the origin of recruits, and acknowledging the mixing of adults, it has been suggested that two substocks might exist (Glaister et al. 1990). However, genetic studies indicate that the eastern king prawn population is comprised of a single stock (Chan 2015) and exhibits strong stock connectivity throughout its range (Montgomery 1990; Taylor et al. 2020). In this assessment the population is treated as a single stock.

Relative to other marine taxa EKP are short-lived but within the penaeid species are one of the largest and long-lived. The growth rates for EKP are greater at higher latitudes and during summer (Lloyd-Jones et al. 2012). EKP are a fast-growing species, growing up to 73 mm and 52 mm carapace length (CL) for females and males respectively and living for up to 3 years (Lloyd-Jones et al. 2012).

Female EKP mature from around 38–42 mm carapace length at around 4 months of age (Courtney et al. 1995; Courtney et al. 1996; Lloyd-Jones et al. 2012). Most spawning occurs from northern New South Wales to south-eastern Queensland. Studies on the reproductive biology of females reported that spawning may take place at any time during the year (Montgomery et al. 2007). However, in Queensland only the winter egg production produces larvae that recruit into the stock (Montgomery et al. 2007; Courtney 1997).

The historical harvests of EKP date back to the early 1900s. Early harvests were relatively small ($<$ 200 t) and it was not until the 1950s when the EKP fishery developed. Harvest data from 1958 was assumed for the modelling purposes to represent the commencement of significant fishing mortality (i.e. near virgin state of EKP).

Fishing for EKP occurs mainly in New South Wales and Queensland as part of two fisheries: Ocean Prawn Trawl Fishery in New South Wales and the East Coast Otter Trawl Fishery in Queensland. EKP have been harvested at depths up to 300 metres, but most harvest occurs between 40 and 200 metres. It is a valuable commercially-fished stock, with harvests at approximately 3000 tonnes of EKP annually in the last five years, with a total annual landed value of about AUD$51 million in 2017–18 (Australian Bureau of Agricultural and Resource Economics and Sciences 2018). The state governments manage their jurisdictions independently and use a range of input controls including vessel entry limitations, boat-day/effort-unit allocations, vessel and gear size restrictions and spatial-seasonal closures.

Regulating catch via output controls is ineffective because prawns are short lived species and biomass can fluctuate (Dichmont et al. 2010b). Management of the EKP fishery in Australia has moved towards more profitable procedures based on effort (number of boat-days) rather than managing the catch against maximum sustainable yield (MSY) (Dichmont et al. 2010a; Punt et al. 2010). Effort quota was implemented in New South Wales in 2019 (Table 1.1). In Queensland, management is considering adopting maximum economic yield (MEY) and boat-days to estimate the effort reference points for the fishery. There are effort caps in the Queensland East Coast Otter trawl fishery including specific effort caps for Great Barrier Reef Marine Park. At present there are no restrictions in place to regulate how much of this overall effort cap is used by the fleet to target EKP in any given year. In New South Wales, recent changes have shifted the main management approach for the species to unitised effort quota for the Ocean Prawn Trawl Fishery (although various gear and spatial restrictions apply).

Table 1.1: Management changes applied to eastern king prawn fishery in New South Wales and Queensland waters

Year	Fisheries Management, Regulations and Operations
Queensland	
1980	1400 licence vessels
1988	Compulsory commercial catch logbook reporting of catch commenced
1999	Introduction of East Coast Trawl Management Plan Reduction of licence operators from 1400 to 800 vessels
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 licence operators to 527 vessels Compulsory commercial logbook reporting of gear commenced Vessels use of computer mapping and global positioning systems Reduction of licence operators to 527 vessels Use of bycatch reduction devices and turtle exclusion devices
New South Wales	
1997	Commercial logbook reporting requirements change
2006	Introduction of Ocean Trawl Share Management Plan
2009	Commercial logbook reporting change from monthly to daily reporting
2019	Finalised New South Wales Business Adjustment Program unitised Ocean Prawn Trawl effort quota

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 52% from 1989 to 2010 (Courtney et al. 2014).

Previously, two models were implemented: a length-spatial model and a delay-difference model. Using these models the biomass ratio was estimated at 60–80% and 75% respectively (Courtney et al. 2014). The current assessment is an update on the previous length-based assessment of the eastern Australia biological stock of EKP, conducted in 2010 (O'Neill et al. 2014; Courtney et al. 2014). The assessment incorporated updated commercial catch, effort, length frequency data and a spatial component that incorporated movement of different size classes to different areas.

The model assessed EKP recruited to offshore waters and excluded juveniles harvested from estuaries and from the Moreton Bay region. The fishing years were defined from month 1 November to 31 October.

This stock assessment aims to determine the status of the biological stock of EKP. It will inform the harvest strategy management and reporting under the Status of Australian Fish Stocks framework (`fish.gov.au`). This report presents estimates of sustainable harvests and effort to ensure the fishery operates at sustainable levels, and support the goals defined in Queensland's Sustainable Fisheries Strategy (Queensland 2017). The goals of the harvest 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

The assessment was spatially stratified into six commercial fishing zones across New South Wales and Queensland, to take into account spatially explicit size distribution of EKP owing to their movement patterns (left map, Figure 2.1). The zones were numbered sequentially from south to north as follows: (1) New South Wales south, (2) New South Wales central, (3) New South Wales north, (4) Queensland south, (5) Queensland central, (6) Queensland north. An additional zone (zone 4s, not shown on the map) is located within the shallow water of zone 4 and was the location of a fishery independent survey of pre-recruit prawns (5–40 mm CL, details provided in Section 2.5.2). Each zone was further subdivided into smaller areas and the data from these specific areas (highlighted on the right map in Figure 2.2) were used toward the analysis of catch rates and fishing power.

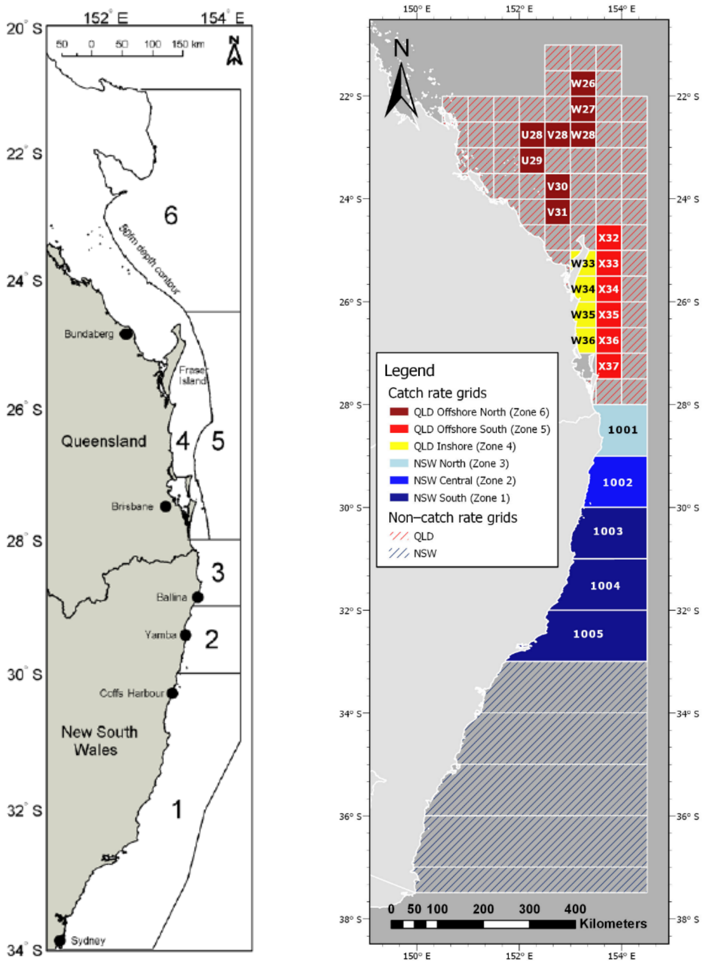

Figure 2.1: Fishing grids corresponding to catch rate analyses for New South Wales and Queensland waters, the map on the left presents the zones and the map on the right presents the grids within each zone used for the catch rate analysis

2.2 Data sources

The data sources included in this assessment (Table 2.1, Figure 2.2) were used to determine catch rates, and to create total annual harvests and size compositions. The time series of data varied between different data sources with harvest data having the longest time series of 60 years from 1959 to 2019.

Table 2.1: Data sources compiled for input into the population model

Type	Years	Source
Commercial Queensland	2004–2019	CFISH – Logbook catch data collected by Fisheries Queensland
	1988–2010	Survey – gear data collected by Fisheries Queensland
	1968–1988	QFISH – catch data
Commercial New South Wales	1984–1997	ComCatch – Logbook catch data New South Wales (monthly reporting)
	1997–2009	ComCatch – Logbook catch data New South Wales (monthly reporting)
	2009–present	FishOnline – (daily reporting)
Fishery independent beam trawl surveys	1999, 2001, 2007–2016, 2018–2019	Fishery Monitoring, Fisheries Queensland
Length frequency Queensland	1990, 1993, 2001, 2002, 2009	Commercial length frequency
	1997 (gradings), 2006–2007 (gradings)	Commercial catch grading data
Length frequency New South Wales	1991, 1992, 2006, 2007, 2015, 2016, 2019	New South Wales port monitoring
Lunar	January 1991–May 2020	O'Neill and Leigh (2006) – continuous daily luminous scale of 0 (new moon) to 1 (full moon)

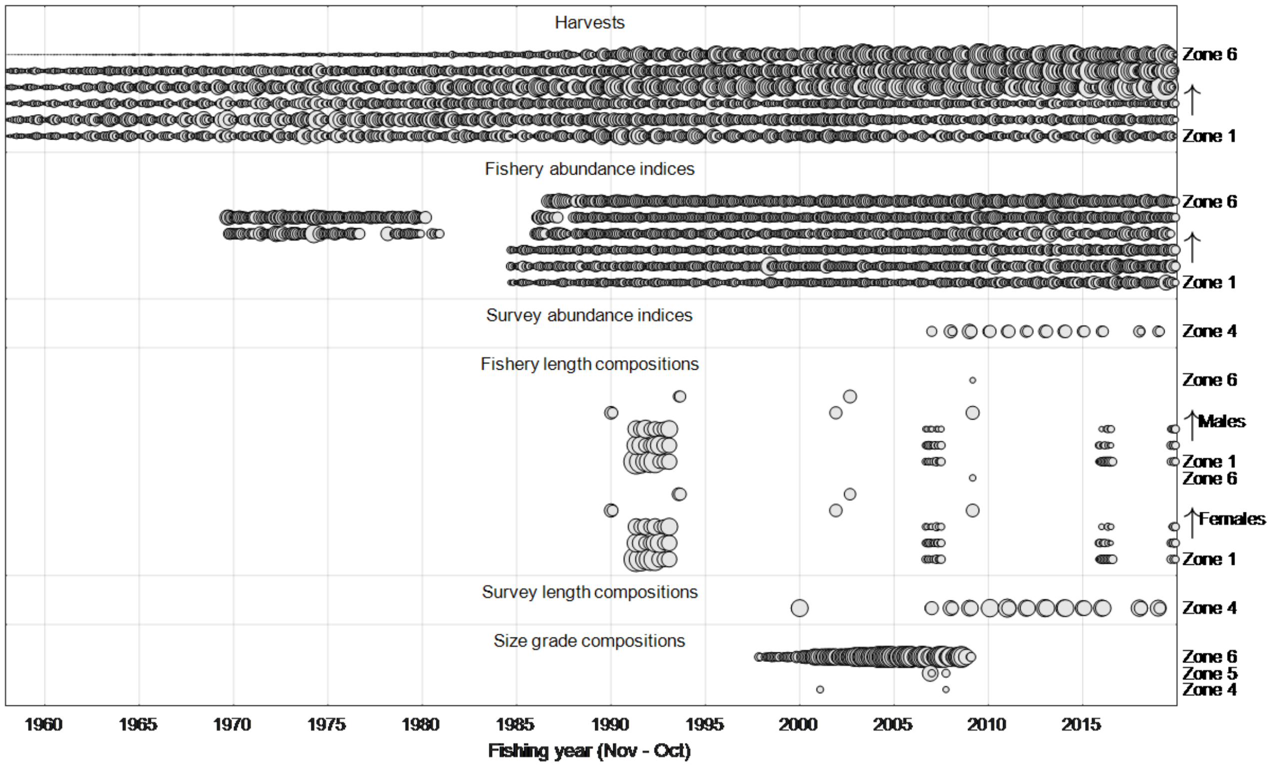

Figure 2.2: Data sources compiled for input into the population model for each month within a fishing year
Note: Circle sizes represent the number of observations and are relative within a data type

2.2.1 Commercial

Commercial catch and effort data were sourced from the New South Wales and Queensland Fisheries compulsory logbook records, 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.1). Up until 2009 the New South Wales data were monthly and daily catch and effort in New South Wales became available after 2009.

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.

Historical commercial harvest data from (pre-1988 catch effort data) were previously obtained from the Queensland Fish Board annual catch data and reported in Courtney et al. (2014). These daily entries for each boat for harvest in kilograms, the geographic location (30' grids) were used as an input to the assessment to generate a continuous time series of standardized catch rates dating back to 1969.

2.2.2 Fishery independent beam trawl survey

Fisheries Queensland conducts a fishery-independent beam trawl survey in southern Queensland to determine the abundance of small-sized EKP (Fisheries Queensland 2016a, 2016b, 2019). This survey is used to inform stock assessment and management about the abundance of pre-recruit size of EKP. The survey runs in November and December each year and has been conducted 13 times since 2006. Survey sites are located in key pre-recruit EKP habitats between 24° 30' S and 28° S (Bessell-Browne et al. 2020). Carapace length compositions of EKP obtained from the beam trawl survey are presented in Appendix B.3.2 (Recruitment). EKP were measured individually to the nearest 0.1 cm.

2.2.3 Length frequency data

Length frequency datasets included fishery specific size classes (15–75 mm) and pre-recruit size classes (0–40 mm). Three size-structured data types were used to calibrate EKP lengths within model:

1. commercial size carapace length frequencies (15–65 mm)
2. large commercial size grade frequencies (34–75 mm) (O'Neill et al. 2014; Courtney et al. 2014)
3. pre-recruit length frequencies (0–40 mm) from fishery independent beam trawl surveys

Updated length frequency data was provided for New South Wales and Queensland survey data. Together the frequencies calibrated regional and monthly changes in EKP size, to estimate prawn length-selectivity and economics. New South Wales EKP carapace length frequencies were recorded from port monitoring of commercial harvest. Sex and carapace length information are presented in Appendix B.3.2 (Length Structures).

2.3 Harvest estimates

Most of the Queensland EKP fishery considered in the assessment is within the Southern Offshore Trawl Fishery management region. For modelling purposes harvest data from 1958 were assumed to represent the commencement of significant fishing mortality (i.e. near virgin state of EKP). Monthly harvests from 1958 to 2019 were reconstructed from Queensland and New South Wales commercial logbook records (Table 2.1). Daily effort information from the Queensland commercial logbooks and New South Wales Fishonline records were aggregated to days per months. The commercial catch was summed from a total of 86 Queensland grids and 12 New South Wales latitudinal bands.

2.4 Fishing power estimates

Fishing power estimates were based on Queensland EKP trawl logbook data consisting of daily catch and effort information per vessel (1988–2019), and combined survey (1988–2004) and logbook data sources (2004–2019) on gear and vessel information. The estimates of fishing power were from data covering fourteen 30' x 30' grids, consistent with the previous assessment (Figure 2.1) and were consistent with the previous analysis of fishing power (Courtney et al. 2014).

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 factors was selected to be used in the subsequent linear mixed model.

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

- engine rated power
- net type
- otter boards
- gear type
- use of try-gear
- bycatch reduction devices and turtle excluders
- global positioning systems

Fishing power and gear effects were estimated for two depth sectors: $\leq$ 50 fathoms deep (shallow water; inshore zone 4) and waters $>$ 50 fathoms deep (offshore north and offshore south, zones 5 and 6 combined). These zones pertain to Queensland fishery.

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 and the interaction with two 'depthsector' terms (as part of a further retrospective analysis summarised below). 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.

Two additional variables were added to the generalised linear model to interact with the gears: 'depthsector1' and 'depthsector2'. 'Depthsector1' is a factor that consists of three levels (zone 4, zone 5, zone 6) and 'depthsector2' is a factor that consists of two levels ($\leq$ 50 fathoms deep (shallow) and waters $>$ 50 fathoms deep (deep). The variable 'depthsector1' is used in the interaction with gears in all Queensland zones (zone 4 to zone 6). The variable 'depthsector2' is only used in the interaction with waters $\leq$ 50 fathoms deep (shallow water sector) and waters $>$ 50 fathoms deep (deep water sector).

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 zone to obtain mean annual estimates of fishing power for each zone on the log scale.

Following this, the estimates of fishing power were summarised for each year by depth sector, and scaled to express relative fishing power in each year as a proportional change relative to the base reference fishing year considered which was 1989; as reported by O'Neill et al. (2003).

Relative fishing power was thus defined using Equation 2.3, representing relative fishing power within each zone:

$$F_y = \exp\left(fp_{yz} - fp1989_{z=4}\right) \tag{2.3}$$

where y is year and z is zone.

2.5 Abundance indices

2.5.1 Commercial standardised catch rates

Standardised catch rate analyses were carried out separately for New South Wales and Queensland stocks. For Queensland catch rate standardisation, 18 grids were selected (Figure 2.1), and for New South Wales catch rate, 5 grids were selected (Figure 2.1, Table B.2). Grids were based on where most of the harvest occurred, and all covered the general movement patterns and geographical distribution of the species.

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).

For the New South Wales catch rate the following model was used:

$$Log(catch_{fp}) \sim fyear * fmonth * zone + zone.logwh + zone.logdays + random = ACN \tag{2.4}$$

For the Queensland catch rate the models used was:

$$Log(catch_{fp}) \sim fyear * fmonth * zone + zone.lunar + zone.lunar_adv + zone.loghrs + random = ACN \tag{2.5}$$

where $Log(catch_{fp})$ is the catch adjusted for fishing power. Three analyses were required according to whether the years and jurisdictions had gear and vessel data (Table 2.2). Analysis 1 was used for Queensland zones 4 to 6 in the years 1989 to 2019 because there gear and effort data was available. Analysis 2 was used for the same zones in Queensland but for the years which had no gear and vessel data. Analysis 3 was used for New South Wales as no gear and vessel data was available.

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

	Analysis 1	**Analysis 2**	**Analysis 3**
Jurisdiction	Queensland	Queensland	New South Wales
Zones	4 to 6	4 to 6	zones 1 to 3
Years	1989 to 2019	1969 to 1988	1984 to 2019
Fixed terms	$\beta_0 + X_1\beta_1 + X_2\beta_2 + X_3\beta_3 + X_4\beta_4$	$\beta_0 + X_1\beta_1 + X_3\beta_3 + X_4\beta_4$	$\beta_0 + X_1\beta_1 + X_4\beta_4 + X_5\beta_5$
Random terms	$Z_1\gamma_1 + Z_2\gamma_2$	$Z_1\gamma_1 + Z_2\gamma_2$	$Z_1\gamma_1$
Fishing power offset	EKP log fishing power from β_2	Linearly hind-cast of deep and shallow water EKP log fishing power from β_2, analysis 1	Combined deep and shallow water EKP log fishing power from β_2, analysis 1, and 1984–1988 linearly hindcasted
Predictions	β_1	β_1	β_1

Analysis 1 was completed to estimate the annual gear fishing power trend X_2 for β_2 by zone (Table 2.2). For analyses 2 and 3, the annual gear fishing power data X_2 was inserted as an offset (Table 2.2). The offset was the estimated log fishing power β_2 for deep and shallow water EKP from analysis 1, with linear values hindcasted for 1969 to 1988 (fishing power fixed terms only; Braccini et al. (2012a)).

As New South Wales catches were reported monthly, no lunar or grid effects could be fitted in analysis 3. Also, the corresponding New South Wales trawl whiting (*Sillago robusta* and *S. flindersi*) catch effect was estimated to adjust for logbooks combining monthly effort for EKP and these alternative target species. This targeting/logbook effect was not present in Queensland waters (zones 4 to 6).

Standardised catch rates were predicted from the 3-way β_1 interaction term, which provided abundance indices for each fishing year, month and zone. Catch rates were predicted relative to the pre-estimated level for lunar and vessel identification (for method refer to Courtney et al. (2014))

2.5.2 Fishery independant survey

The standardised abundance index for EKP was generated from the fishery-independent beam trawl survey. This represented data sampled from in and around Moreton Bay. The beam trawl survey is reported in Bessell-Browne et al. (2020). The catch rate index of abundance includes all EKP $>$ 0 mm carapace length in the months of November and December (detailed in the Appendix B.3.2).

2.6 Selectivity

The length-frequency data was filtered to include specific size classes and caught by otter-trawl only. Once the data were filtered the length frequencies for each size class were estimated as proportions (of the total number) caught for each year and total number caught for each year.

For New South Wales Port samples, lengths between 0 mm and 79 mm were in 1 mm increments. For Queensland two data sets on size structure were used: carapace length frequencies and commercial size-grade frequencies. Together, these data sets quantified regional and monthly changes in EKP size.

The lengths used were carapace length, measured from the post-orbital margin to the posterior edge of the carapace. The carapace length frequencies were recorded onboard commercial fishing vessels. Each prawn was sexed and measured to 1 mm length classes. From New South Wales, summaries of monthly length frequencies existed from a previous dataset for a continuous 24 month period (1991–1992, zones 1 to 3). Additional length frequencies provided were sporadic through time (2006, 2007, 2015, 2016, 2019). Monthly length frequencies from Queensland waters were sporadic through time (zones 4 to 6, Table 2.3). For zone 6 additional length frequency data was provided in the form of grading data (Courtney et al. 2014). To summarise, the grading categories were as follows:

- $>$30 ($>$30 prawns per pound equating to 1–33 mm)
- 16–20 (16–20 prawns per pound: 34–37 mm)
- 10–15 (10–15 prawns per pound: 38–43 mm)
- 8–10 (8–10 prawns per pound: 44–47 mm)
- 6–8 (6–8 prawns per pound: 48–53 mm)
- under 6 (6 prawns or fewer per pound: 54–75 mm)

Table 2.3: New South Wales and Queensland EKP—description of EKP size-structured data

EKP size data	Zone	Fishing years and months
Carapace lengths (mm)	1,2 and 3	1991–1992, all 24 months
		2006, (Jul–Oct), 2007 (Jan–May, Nov–Dec)
		2015, (Sep–Oct), 2016 (Jan–Jun, Nov–Dec)
		2019, (Jul–Nov)
	4	1990, November and December
		2001, October
	5	1993, June and July
		2002, July
	6	2009, January
Grading categories (1 to 7)	6	September 1997 to December 2008

2.7 Biological parameters

Biological information and parameters use are detailed in Courtney et al. (2014). Most of these parameters have been used again for this assessment (Table 2.4).

2.7.1 Growth

Growth was based on the von Bertalanffy model, however in the assessment, growth was incorporated without a von Bertalanffy model. Instead growth was included as a size transition matrix as detailed in Courtney et al. (2014) and formulated on the von Bertalanffy model using parameters adjusted latitudinally and seasonally as described in Lloyd-Jones et al. (2012).

2.7.2 Maturity

Logistic maturity schedule by carapace length (mm) and zone was estimated using binomial regression and logit link as detailed in Courtney et al. (2014). To summarise, data on maturity were collected between autumn 1991 to winter 1992 inclusive, from eight regions in Queensland. Samples of female prawns were randomly collected each month from the catches of commercial fishing vessels. The carapace length of females was measured and the ovaries were examined microscopically for maturity condition and spawning potential. The data was analysed using a linear model with ‘maturity’ as the response variable and ‘length’ and ‘region’ as two of the terms in the linear model:

$$maturity \sim Constant + Year + Month + zone/Length \text{ ; adjusted } R^2 = 0.746 \qquad (2.6)$$

The Genstat model terms $Year$, $Month$ and $Zone$ were factors, while $Length$ was a variate.

2.7.3 Fecundity

Fecundity was included in the model to provide estimates of egg production at length per female EKP and is detailed in Courtney et al. (2014) and Montgomery et al. (2007). Fecundity is given by the equation:

$$f = 10^{al+b} \tag{2.7}$$

2.7.4 Spawning

Proportion of EKP spawning by zone are represented by $\theta = [0.15, 0.33, 0.6, 0.6, 0.6, 0.75]$ and described in Montgomery et al. (2007).

2.7.5 Length to weight

The average weight in kilograms at length (mm) for sex is given by the equation:

$$wt = a * l^b \tag{2.8}$$

2.7.6 Pre-recruits

The beam trawl survey data was used to estimated the size range to be used to recruit the first cohort into the model. The method is described in Courtney et al. (2014). To summarise, the survey length data was analysed to obtain size frequencies of 1 mm size classes and further analysed to determine smallest cohort to subsequently recruit into the model. This spreads out the size distribution of the first cohort into a realistic size range which will eventfully grow through the size classes more naturally than imposing a given schedule.

Recruitment is introduced into the model as a single cohort with normal distribution mean (μ) = 15.5 mm and standard deviation (σ) = 6.3 mm. Recruitment into the model was a pulse recruitment that occurred in one month rather than being distributed over several months.

Table 2.4: Biological parameters used in the eastern king prawn model

Parameter	Value	Comments
Natural Mortality		
M	0.18	One parameter for instantaneous natural mortality per month, with prior distribution 0.18 and se 0.05; 0.2 also used in early work, and for tiger prawns and the NPF. The prior distribution allowed for two to three years longevity (Lloyd-Jones et al. 2012), and values around those used in previous EKP modelling (O'Neill et al. 2005; Lucas 1974). Ives et al. (2007) summarised estimates of EKP M ranging from 0.13 to 0.35, with values $\geq$ 0.24 possibly biased upwards (Glaister et al. 1990). Base on pcc rules, used a log se ~0.15 to give little Pr above 0.24.
Maturity		
l_{50}	38	for zones 3,5,6
l_{95}	45	for zones 3,5,6
l_{50}	40	for zones 1,2,4
l_{95}	45	for zones 1,2,4
Fecundity		
a	0.0199	Fecundity (egg production) at length per female EKP (Courtney 1997; Montgomery et al. 2007).
b	4.7528	see Equation 2.7.
Proportion spawning		
sp1	0.15	Proportion of EKP spawning by zone (Montgomery et al. 2007); (Figure 17–40). sp zone1
sp2	0.33	zone2
sp3	0.6	zone3
sp4	0.6	zone4
sp5	0.6	zone5
sp6	0.75	zone6
Length to weight		
male_a	0.0017	Average EKP weight (g) at length l for sex s (Courtney 1997) / 1000 for kgs
male_b	2.7005	see Equation 2.8
female_a	0.0021	
female_b	2.6333	

2.8 Population model

2.8.1 Population dynamics

The EKP population model had a monthly time step and tracked numbers (N) and biomass (B) of prawns by their sex (s) and length (l), and included the processes of mortality, growth and recruitment in every month (t).

The model dynamics were structured such that the following processes occurred through a month/year and zone:

- Half natural mortality, fishing mortality (exploitable biomass B^1), half natural mortality (exploitable biomass B^2), Growth, movement, recruitment (half for each sex) (see table 17.3 of Courtney et al. (2014))

- Exploitable biomass was calculated 'mid-month' before fishing and after fishing. This was done to calculate:
  - harvest rates using half of natural mortality M to estimate exploitable biomass before fishing (type B^1).
  - catch rates by applying half of the harvest rate to B^1 to calculate exploitable biomass after fishing (type B^2). Catch rates estimated from B^2 were used to fit to the observed catch rates.
- Recruitment is introduced into the model as a single cohort with normal distribution mean (μ) = 15.5 mm and standard deviation (σ) = 6.3 mm.
- The catch rate indices were fitted to the vulnerable biomass calculated after 50% of the catch is taken. A common alternative is to modify the assessment model so that fits to the catch rate indices are calculated after 50% of the fishing and 50% natural mortality have occurred.

The model was run in two phases:

1. historical estimation of the EKP stock from 1958 to 2010 and
2. simulations of EKP parameter values and uncertainty to evaluate reference points and management procedures.

In order to calibrate the model, estimated model parameters were calibrated to regional standardised catch rates and size-composition data (for a list of estimated and fixed parameters see Table 2.5). Primary importance was placed on fitting the abundance (standardised catch rates) data well (Francis 2011). Effective sample sizes were estimated for scaling multinomial likelihoods in order to calibrate to the size composition data.

Following the previous 2010 assessment, a penalty function was included to prevent unrealistically large population estimates and low harvest rate estimates. Prior fitting information was given for fixed the natural mortality (M = 0.18). Goodness-of-fit plots were examined to evaluate model fits. The maximum likelihood parameter estimates and their covariance matrix were stored for estimating reference points and running simulations.

Number of prawns

$$N_{l,r,t,s} = \exp(-M) \sum_{r'} T_{r,r',t-1} \sum_{l'} \Xi_{l,l',r',t-1,s}(1 - v_{l',r'} u_{r',t-1}) N_{l',r',t-1,s} + 0.5 R_{l,r,t} \tag{2.9}$$

Egg production (also spawning biomass) — annual number of eggs

$$E_y = \Sigma_t \Sigma_r \Sigma_l N_{l,r,t,s} m_{l,r} f_l \theta_r \tag{2.10}$$

Recruitment pattern — normalised monthly proportion

$$\phi_t = \exp[\kappa \cos(2\pi(t-\mu)/12)] / \sum_{t'=1}^{12} \exp[\kappa \cos(2\pi(t'-\mu)/12)], \tag{2.11}$$

where t indicated time-of-year months 1...12, μ and κ are estimated parameters representing the mode and concentration of the monthly recruitment pattern according to a von Mises directional distribution (Mardia et al. 2009).

Recruitment numbers — Beverton-Holt formulation

$$R_{l,t} = \frac{4hR_0\tilde{E}_{y-1}}{E_0(1-h)+\tilde{E}_{y-1}(5h-1)}\phi_t \Lambda l \exp \mu_y, \tag{2.12}$$

where y indicated the fishing year, Λ_l is the recruitment proportion for each length class, $\exp \nu_y$ represents estimated recruitment deviations, R_0 represents virgin recruitment, and h is the Beverton-Holt steepness parameter (Beverton et al. 1957). This steepness parameter, h, is calculated from the estimated parameter ξ as follows:

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

$$r_{\text{max}} = 1 + \exp(\xi) \tag{2.14}$$

Virgin recruitment R_0 was estimated on the log scale using the parameter γ as follows:

$$R_0 = \exp(\gamma) \times 10^8 \tag{2.15}$$

Mid-month exploitable biomasses—forms 1 and 2

$$B^1_{r,t} = \Sigma_l \Sigma_s N_{l,r,t,s} w_{l,s} v_{l,r} \exp(-M/2) \tag{2.16}$$

$$B^2_{r,t} = \Sigma_l \Sigma_s N_{l,r,t,s} w_{l,s} v_{l,r} \exp(-M/2)(1 - u_{r,t}/2) \tag{2.17}$$

Harvest rate

$$u_{r,t} = C_{r,t}/B^1_{r,t} \tag{2.18}$$

where C was the monthly harvest (kgs) for each zone and B is exploitable biomass.

Selectivity: fishery

$$v_{l,r} = \frac{1}{1 + \exp(\delta(l^{50}_r - l))} \tag{2.19}$$

Selectivity: survey zone 4s

$$v^{\text{survey}}_l = \frac{\max\left[\frac{1}{d_1}(\delta^{\text{survey}} + \frac{1-\delta^{\text{survey}}}{d_2}), 0\right]}{\max_l\left[\frac{1}{d_1}(\delta^{\text{survey}} + \frac{1-\delta^{\text{survey}}}{d_2})\right]} \tag{2.20}$$

$$d_1 = 1 + \exp(-\log(19)\frac{l - l^{50}_{\text{rising}}}{l^{\text{diff}}}) \tag{2.21}$$

$$d_2 = 1 + \exp(-\log(19)\frac{l - l^{50}_{\text{falling}}}{l^{\text{diff}}}) \tag{2.22}$$

Dome-shaped selectivity requiring four estimated parameters, where l^{50}_{rising} denotes length at 50% selection by the survey on the upward slope, l^{50}_{falling} denotes length at 50% selection by the survey on the downward slope, l^{diff} denotes the difference between the length at 50% selection by the survey and 95% selection and δ^{survey} denotes the asymptote past the dome.

2.8.2 Model assumptions

The following assumptions were made when formulating the population model:

- Length refers to carapace length.

- Prawns spawning was based on female only and was assumed to occur in varied fractions throughout the fishery zones (Courtney et al. 2014).
- Fishing takes place in the middle of each month.
- The proportion of mature prawns depended on length.
- Recruitment ratio of males to females was 50%.
- The fishery-independent beam trawl survey index of recruitment abundance is representative of the zone 4 fishery.
- Prawn movement from zone 4 to zone 6 was estimated based on movement from zone 4 to zone 5. Prawn movements varied by fishing month and zone, but were the same between years.
- EKP growth, maturity and length-to-weight conversion is as reported in Courtney et al. (2014).
- The biological parameters used in this stock assessment is assumed to be representative of the current stock.

2.8.3 Model parameters

Table 2.5: Descriptions of estimated and fixed parameters in the model

Parameter	Value (se)	Description
ξ	estimated	Used to determine Beverton-Holt steepness h (Equation 2.13)
γ	estimated	Used to determine R_0 (Equation 2.15)
μ	estimated	Mode of the monthly recruitment pattern (Equation 2.11)
κ	estimated	Concentration of the monthly recruitment pattern (Equation 2.11)
$l^{50}_{f,s}$	estimated	Length at 50% selection by fishing area. Only 3 parameters estimated. Inshore and Offshore Region for males and a shared parameter for Inshore/Offshore Region females (Equation 2.19)
δ	estimated	Initial steepness of the vulnerability curve (Equation 2.19)
l^{50}_{rising}	estimated	Length at 50% selection by the survey on the upward slope (Equation 2.14)
l^{diff}	estimated	The difference between the length at 50% selection by the survey and 95% selection (Equation 2.14)
l^{50}_{falling}	estimated	Length at 50% selection by the survey on the downward slope (Equation 2.14)
δ_{survey}	estimated	Asymptote for survey vulnerability (Equation 2.20)
ς	estimated	Two parameters denoting catchability amplitude
θ	estimated	Two parameters denoting the peak timing of catchability
nllp	0 (0.005)	Standard deviation std for any -LL penalties
sigRlow	0 (0.1)	Lower bound on annual recruitment std (O'Neill et al. 2014)
sigRup	0 (0.5)	Upper bound on annual recruitment std (O'Neill et al. 2014)
rec_fyr	1970 (0)	First year to estimate recruitment deviations
sigma1	0 (0.1)	NSW zones 1 to 3 minimum log cpue stddev for nll; generalised from reml log preds; taken as min(zone 2 preds)
sigma2	0 (0.06)	Qld zones 4 to 6 minimum log cpue stddev for nll; generalised from reml; for post-1987 logbook data; min(zone4) $\sim$ median
sigma3	0 (0.12)	Qld zones 4 to 6 minimum log cpue stddev for nll; generalised from reml; for pre-1988 htrawl logbook data; median(zone4) as varied ses
sigma4	0 (0.08)	Survey zone 4 min log cpue stddev for nll; min log ses

2.8.4 Matching predictions to data

In order to realise the operating model, parameters were estimated to calibrate the model to zone specific standardised catch rates and size-composition data. Primary importance was placed on fitting the abundance (standardised catch rates) data well (Francis 2011). Effective sample sizes were estimated for scaling multinomial likelihoods in order to calibrate to the size composition data. Following the 2010 assessment, a penalty function was included to prevent unrealistically large population estimates and low harvest rate estimates. The model and data fitting negative log-likelihoods were described by O'Neill et al. (2014). The calibration process used maximum likelihood estimation. The maximum likelihood parameter estimates and their covariance matrix were stored for estimating reference points and running simulations for confidence intervals. Goodness-of-fit plots were examined to evaluate model fits.

2.8.5 Model uncertainty

Confidence intervals on all outputs were generated by a Monte Carlo routine of running the models for 2000 variations in the parameters estimated (Richards et al. 1998; O'Neill et al. 2005). The algorithm used to generate 95% confidence intervals was to:

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 parameters).
5. Repeat the process from step two to four 2000 times to obtain a large number of 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

EKP catch data for New South Wales and Queensland show that most of the catch occurred in two zones: zone 5 (Queensland offshore south), and zone 6 (Queensland offshore north). These zones are within the Southern Offshore zone (Figure 2.1). Harvests increased markedly in 1989 in all zones and have since steadily increased (with fluctuations). The highest annual catches of EKP occurred over 1999–2019, with episodic peaks in catches followed by sharp declines.

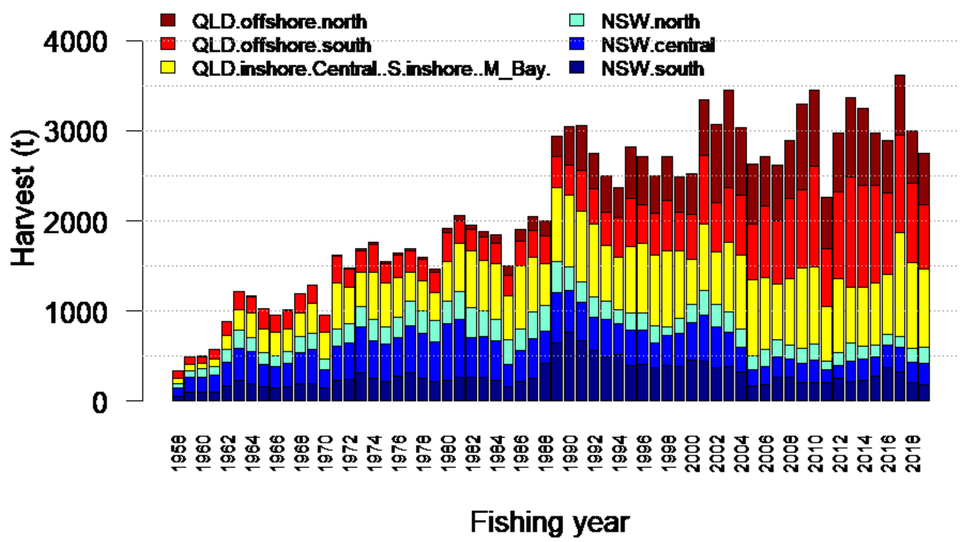

Figure 3.1: Total reported annual landed catch of EKP from 1958 to 2019

3.1.2 Fishing power

Fishing power in the EKP fishery was found to have increased in all Queensland zones from 1989 to 2019 (51% Queensland inshore, 37% Queensland offshore south, 49% Queensland offshore north, Figure 3.2) highlighting the need to take fishing power into account when reporting long-term trends in catch rates, and assessing the stock.

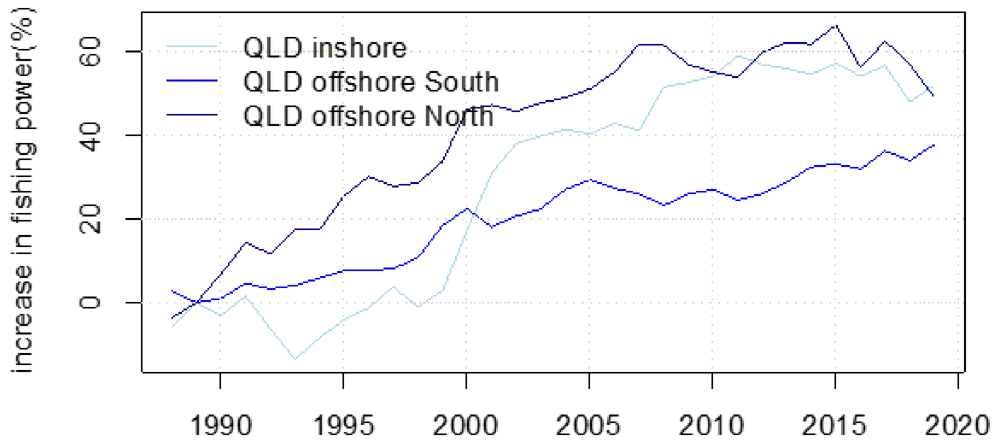

Figure 3.2: Increase in fishing power for the Queensland EKP fishery

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 characteristic resulted in increased in fishing power: higher engine rated power, adoption of BRDs and TEDs, the use of quad net gear, drop chains and their variants.

3.1.3 Abundance indices

3.1.3.1 Commercial standardise catch rate indices

Catch rates were standardised to represent trends in the abundance of EKP and trawl fishing power averaged for 2010–2019 (Figure 3.3). Annual catch rates have steadily increased since 1988 in New South Wales and Queensland, with Queensland having higher catch rate than New South Wales. Within Queensland, the annual catch rate was lower for inshore than offshore regions. There was a sharp increase in the standardised catch rates in all zones between 2007 and 2010, followed by regular fluctuations since 2010. In Queensland, catch rates for zones 5 and 6 have decreased since 2015 and have since stabilised. Interestingly within New South Wales the annual catch rate increased over the last 14 years narrowing the difference (in kg) between New South Wales and Queensland.

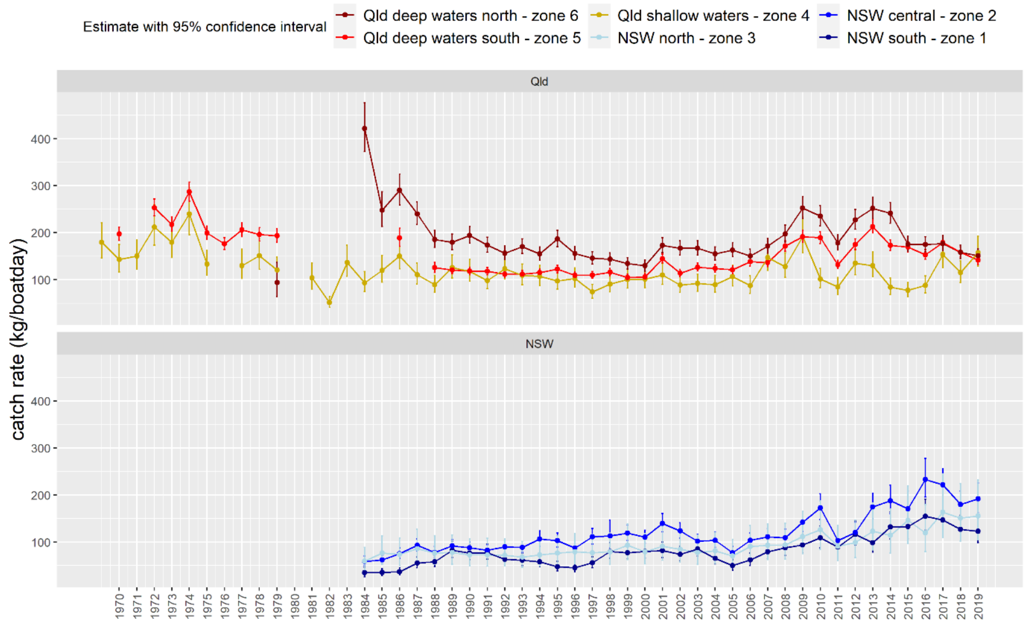

Figure 3.3: Annual standardised catch rates (and 95% confidence intervals) for New South Wales and Queensland EKP

Monthly catch rates were used as a model input, and reported in Appendix B.2.

3.1.3.2 Survey abundance indices

Results from the survey abundance indices reveal strong differences in abundance within 2007, 2008 and 2017, with higher abundances in the first month compared to the second month of the survey. This strong inter-monthly variation might be due to trends in prawn movement whereby prawns move away from this region over the course of a month (Figure 3.4).

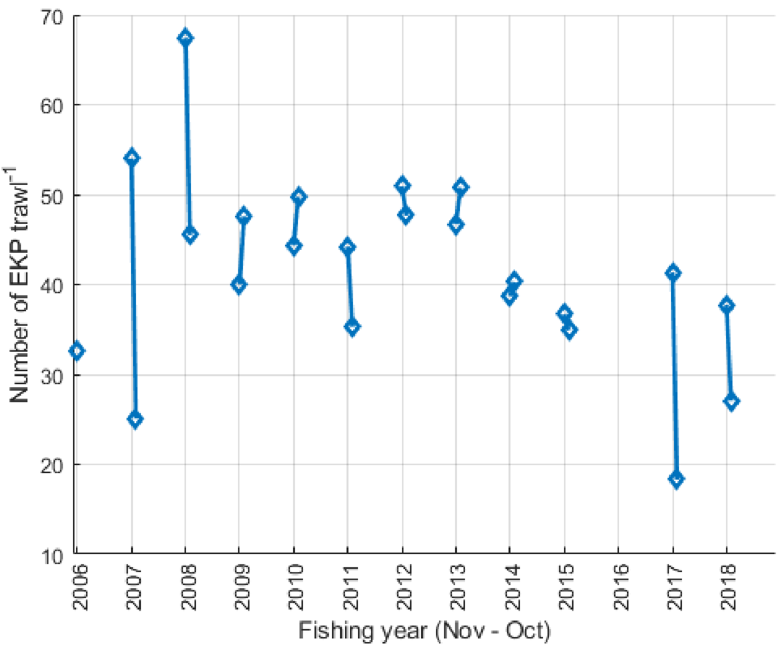

Figure 3.4: Fishery independent abundance data from beam trawl surveys

3.1.4 Length frequency

In general the length-frequency data revealed that smaller prawns were more common in the southern-most zone of New South Wales (zone 1) and the median size increased in the more northern populations (zones 5 to zone 6, Figure B.4). In zone 4 (southern Queensland) the sizes were smaller revealing a possible source of new recruits in the form of smaller size prawns and this is consistent with the fishery independent length frequency data where size range was 5–40 mm CL (Figure B.7).

The gradings data represented size frequencies from the zone 6 (the northern most zone in Queensland) where lengths are reported to be relatively higher compared to the other zones. Consistent with the length frequency data higher lengths were observed with the majority of prawns were between 48–53 mm CL and the maximum range was between 54–75 mm CL (Figure B.5)

3.1.5 Pre-recruits

In the present modelling, a size range from 0–40 mm in 1 mm size classes was used. This was informed by the beam trawl survey length frequency data which was used to provide realistic information on the size classes and their frequencies.

3.2 Model outputs

Results from the model outputs are informed by the different EKP input data for monthly harvests, catch rates and size compositions.

3.2.1 Model parameters

In total there were 78 parameters estimated by the model including 49 for calculating annual recruitment, 4 for initial recruitment, 7 for seasonal catchability, 11 for selectivity, 6 for seasonal recruitment relationship, and 1 for transformed steepness of the Beverton-Holt equation. The parameters are listed in Table 3.1 except for the 49 recruitment coordinates. There were two fixed parameters: natural mortality ($M = 0.18$) per month, and the zone 4 survey domed vulnerability asymptote (= 0). Growth parameters were predetermined and built into the size transition matrix which was used for growth.

Table 3.1: Estimated model parameter values, excluding the 49 recruitment coordinates

Parameter	Zone	Description	Value	Standard error
ξ	all	Used to determine Beverton-Holt steepness h	-1.144851911	0.11474757
γ	zone 1	Used to determine R_0	0.623425237	0.096477963
	zone 2		1.94096769	0.113729635
	zone 3		2.794483245	0.09908611
	zone 4		1.654379038	0.08889112
μ	zone 1	Mode of the monthly recruitment pattern	4.246935698	0.100917756
	zone 2		4.432916343	0.135461109
	zone 3		9.053631633	0.109967553
	zone 4		1.379666194	0.107481858
κ	zone 1:3	The concentration of the monthly recruitment pattern	0.943890711	0.085970565
	zone 4		4.329404822	0.097632487
l^{50}	zone 1	Length at 50% selection	33.1372236	0.116422522
	zone 2		31.49514739	0.136678844
	zone 3		38.19410808	0.095764718
	zone 4		26.19032259	0.094620754
	zone 5		38.19403664	0.098972871
	zone 6		38.19373214	0.085307572
δ	all	Initial steepness of the vulnerability curve	0.368503448	0.03564388
l^{50}_{rising}	all	Length at 50% selection by the survey on the upward slope	26.19032854	0.108981371
l^{diff}	all	Difference between the length at 50% selection by the survey and 95% selection	12.86228475	0.106344733
l^{50}_{falling}	all	Length at 50% selection by the survey on the downward slope.	32.48686727	0.114465745
ρ	all	Parameter for estimating movement from zone 4 to 6	-0.635519855	0.105611243
ς_1	all	Catchability amplitude 1	-0.311932237	0.047826791
q	zone 1	Catchability seasonal modes	0.47567939	0.122058956
	zone 2		-0.648887509	0.137498296
	zone 3		-2.291986976	0.129511209
	zone 4		-0.731006169	0.126608232
	zone 5		-0.629535402	0.098138846
	zone 6		0.037469998	0.095876852

3.2.2 Model fits

In total 78 parameters were estimated to calibrate the model to zone specific standardised catch rates and length frequency data. The model was fitted to the following data sources and each will be briefly discussed in turn:

- commercial catch rate data for each commercial fishery zone (zone 1 to 6),
- survey abundance indeces from zone 4s,
- length frequency data (female and male) from each commercial fishery zone (zone 1 to 6),
- survey length frequency data from zone 4s, and

- commercial size grade frequencies.

The fits to the commercial catch rates varied between zones. Generally for New South Wales (zones 1 to 3) the predicted monthly catch rates were lower than the observed data after 2014 (Appendix B.2, Figure B.1). The underestimated catch rates from the model are reasonable because the increasing trend may have been partially driven by changing reporting behaviours through time (this is discussed in Section 4.2). For Queensland (zones 4 to 6) the predicted model catch rate fitted the data well and within the range of the observed data with the exception of zone 6 (Appendix B.2, Figure B.2). In zone 6 the predicted estimates from the model were higher than the observed from 2016 onwards. This is likely to result in slightly higher estimates of spawning biomass.

The fits to the survey abundance indices reveal that the model had varied fits to the data. The model consistently fitted the first month of the fishing year better than the second month where the predicted estimate was higher than the observed (Appendix B.2, Figure B.3).

The fits to the length frequency data for zones 1 to zone 5 were good with zone 6 requiring more data to improve the fit (Appendix B.3, Figure B.4). Commercial size grade frequencies were used as an additional length frequency data input for zone 6 and there was good agreement between the predicted estimates from the model and observed data (Appendix B.3, Figure B.5).

The fishery independent survey data was used to determine the size classes to be used to recruit prawns into the model. The final length frequency distribution summarised from the beam trawl survey data depicted the size structure used to recruit prawns into the model. The fit between the observed and model was good across the observed size range. (10–40 mm, Appendix B.4, Figure B.8)

3.2.3 Biomass

The model predicted that historical EKP spawning biomass, expressed as a median ratio of egg production relative to 1958, declined to roughly 50% in 1984–85 and has steadily increased to 62% in 2019 (Figure 3.5). The median ratios have shown greater fluctuations since 2000.

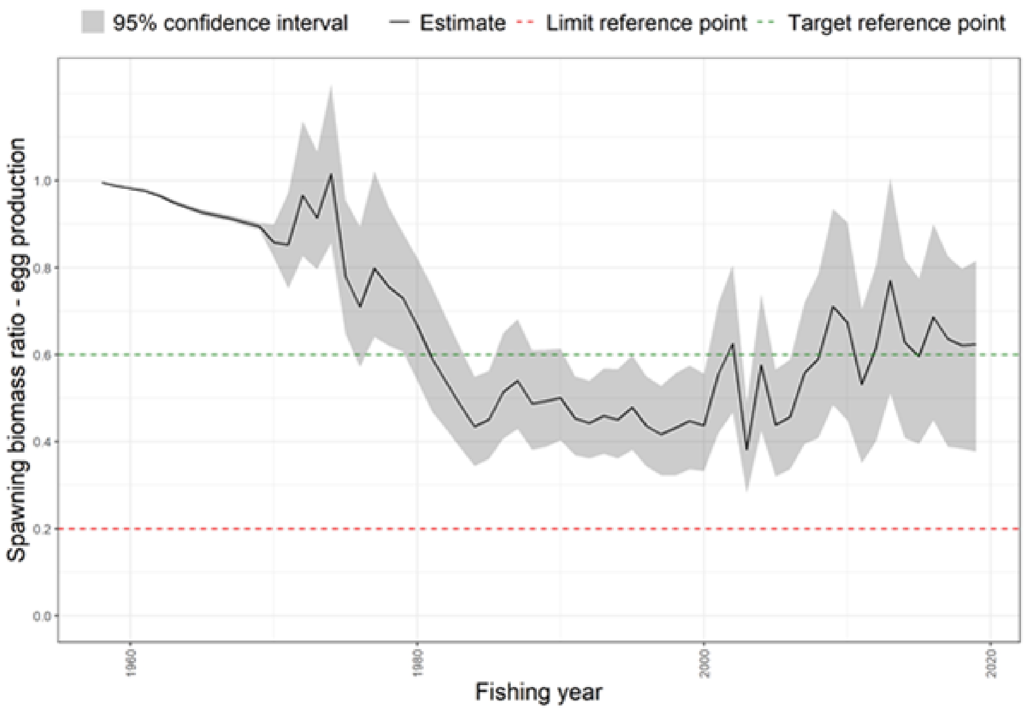

Figure 3.5: Annual biomass, and 95% confidence intervals, for New South Wales and Queensland EKP

3.2.4 Harvest targets

Current harvests, fishing efforts and reference points are detailed in Table 3.1 and the corresponding confidence intervals are provided in Appendix D. The key population performance indicator was an annual estimate of spawning biomass ratio, expressed in terms of spawning egg production by mature female EKP across the whole stock. The annual estimate of maximum sustainable yield (MSY) was 2423 tonnes. The 2019 harvest was 2753 tonnes, slightly above the MSY (2423 tonnes) and the target (2155 tonnes), where 593 tonnes were harvested from New South Wales waters, and 2160 tonnes from Queensland waters. The 2019 effort was 15 940 boat-days/year and is below the median E_{targ} of 16 450 boat-days/year but within the range (11 063–20 008 boat-days/year, Table D.1)

Table 3.2: Description of current performance indicators and reference points for 2019 assessment

Parameter	**Estimate**
Spawning biomass level in 2019 (S_{2019}/S_{1958})	62%
Spawning biomass level at MSY (S_{MSY}/S_{1958})	42%
Spawning biomass level at MEY (S_{MEY}/S_{1958})	69%
Current harvest (2019)	2738 tonnes
MSY	2423 tonnes
Harvest at S_{60}	2155 tonnes
MEY	1786 tonnes
Fishing effort in 2019: standardised	15 940 boat-days/year
E_{MSY}	27 242 boat-days/year
E_{targ}	16 450 boat-days/year
E_{MEY}	11 423 boat-days/year

4 Discussion

4.1 Stock status

Spawning biomass (S) as estimated by the model was 62% in 2019, being slightly above the target reference point (S_{targ}) of 60% and above the (S_{MSY}) of 42%. Therefore the stock is sustainably fished.

Fishing effort (boat-days/year) at 60% spawning biomass (E_{targ}) was 16 450 boat-days/year and fishing effort at E_{MSY} (40% biomass) was 27 242 boat-days/year (standardised to the number of boat-days in 2019). Currently the recorded number of boat-days in 2019 was 15 940 boat-days/year (standardised) which was lower than the target effort (E_{targ}) and E_{MSY} estimate. Using E_{MSY} as a reference point, the stock is sustainably fished.

MSY in 2019 (i.e. yield at 42% biomass) was estimated to be 2423 tonnes and the yield at the target 60% depletion was 2155 tonnes. Currently the total catch in 2019 was 2738 tonnes, being higher than both the MSY and target.

4.2 Performance of the population model

Analysis of standardised residuals indicated that the length-spatial model fitted the data appropriately and that the assumed error structures were valid (Figure B.1, Figure B.2). No concerning correlations of key parameter estimators were evident.

The model predicted the EKP fishery standardised catch rates reasonably well, although the predicted New South Wales catch rates were lower than the observed estimates from the logbook data mainly in the years after 2014 (Figure B.1). It is likely that some of the data from the post-2009 logbook records include aggregative reporting behaviour, whereby catches accumulated across an entire week or month are reported in a single (daily) record, thus resulting in a scenario where the effort associated with a given unit of catch is underestimated. Although this would artificially elevate the observed catch rate, the model underestimated the observed catch rates later in the time series. The underestimation of catch rate means that the outputs may not be substantially affected by aggregative reporting.

For the Queensland standardised catch rates, the predicted estimates were consistent with the observed estimates with the possible exception of Queensland zone 6 (Figure B.2). In this zone the predicted catch rate was higher than the observed for the years after 2014. Given that a high proportion of the records come from Queensland (and zone 6) this might have a bearing on the assessment outputs and artificially elevate the resulting biomass in 2019. This would result in a higher biomass estimate than exists in reality. This needs to be carefully factored in when considering the biomass and it is possible that the estimated result of 62% might not be a conservative estimate.

It is possible that the catch rate is hyperstable if EKP aggregate in schools. The risk of this might be reduced by accounting for fishing power and if the likelihood is that EKP are not aggregating given they are migratory.

One of the key features underlying this assessment is the use of a novel approach when estimating catch rate and fishing power. REML was used in the linear modelling and reference levels in the modelling were explicitly identified. One notable aspect of this assessment is the specific selection of reference points within the Queensland catch rate standardisations and fishing power estimates. The careful selection of reference levels is considered to improve the stability of the catch rate indices and fishing power estimates.

4.3 Fishing power

Fishing power increases were previously recorded to be approximately 3% per year (Braccini et al. 2012b; O'Neill et al. 2007). The number of boats accessing the fishery has remained stable in Queensland since 2012 and has continued to decline in New South Wales.

4.4 Recommendations

4.4.1 Monitoring

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, maturity, length-to-weight and the size composition monitoring data will improve the robustness of the model and provide a more fully-updated assessment.

There is some uncertainty surrounding reported effort levels in New South Wales, following the shift to daily reporting in 2009. Validation of daily logbook reporting would improve confidence in the time series used for catch rate standardisation, particularly for data collected post-2009. Recently implemented real-time effort reporting that is used to track quota usage in New South Wales, provides a secondary source of data to compare with the effort reported in normal logbook records. This may be useful for interpreting effort data in the period post-2019.

An update to the the length gradings frequency data will better inform the length frequency of the Queensland offshore north zone (zone 6).

If the fishery management objectives include economic targets, such as MEY and E_{MEY} reference points, then collection of economic data is required every 5 years.

4.4.2 Management

Considerations for management are as follows:

- E_{MSY} should be considered in the range 27 000 boat-days/year (ranging from 18 535–33 020 boat-days/year) which is associated with 2015–2019 levels of fishing power .
- The uncertainty surrounding the value of E_{MSY} was not unusual for a fishery stock assessment.
- The result confirmed that target fishing efforts should not approach the E_{MSY} limits under consideration of higher risks of overfishing and lower profitable catch rates.

4.4.3 Assessment

The model is a well-designed model that accurately captures the dynamics of the population and the fishery. As with many models, formulating fisheries management plans based on models depends on the nature of the data.

Future analyses could consider removing vessel as a random effect in the catch rate standardisation algorithm, as not all vessels may be reporting effort in the same way. In this assessment, rather than exclusion of any data for this reason, all data was included in the modelling, and the potential implications of aggregative reporting, and its influence on catch rates and model outputs, was discussed.

The length-composition data is fragmentary for EKP in Queensland and New South Wales. The benefits of a comprehensive length-based assessment is that it provides additional information about the stock and can incorporate multiple sources of data. Having additional length frequency data confers advantages over empirical based assessment that rely solely on catch rates.

Further statistical analysis is required to identify any potential relationships between the survey abundance index and the commercial fishery and the contribution of juvenile EKP from inshore Moreton Bay to fishing grounds further offshore in zone 4.

It is recommended that data collected by independent surveys using chartered commercial fishing vessel from New South Wales be incorporated into the next assessment. This consists of sampling of the size structure of early juvenile (20 mm carapace length onward) from inshore waters in New South Wales between 2017 and 2019.

4.5 Conclusions

The EKP fishery is a commercially valuable stock in Queensland and New South Wales. This assessment has informed the status of the eastern king prawn population on the east coast of Australia. The results provide empirical performance measures (catch rates, length frequency, etc) against model based performance indicators (S_{MSY}, S_{MEY}, E_{MSY}, E_{MEY}). Results from this assessment suggest that current harvest levels are in line with the target reference point under the Sustainable Fisheries Strategy. Some limitations of the assessment have been noted and recommendations made.

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Appendix 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 for New South Wales and Queensland

Data	Details	Notes
New South Wales		
HCatch data (pre-01/07/1984)	Catch only data from New South Wales DPI HCatch database	Data provided for the previous assessment (Courtney et al. 2014) were used for this assessment
ComCatch data (01/07/1984–30/06/2009)	EKP catch and effort data provided on 21/4/2020	Fisher data were encrypted. Post-extract processing was undertaken in MS Excel. For Ocean Prawn Trawl data, catch of other species (Whiting, Red Spot/School/Trawl, Octopus, Bugs, Balmain; Squid, Mixed/Unspecified) was matched to each EKP record for catch rate standardisation. Catch and effort records that spanned two Reporting Zones within a monthly record, were split evenly among the zones
FishOnline data (01/07/2009–30/06/2019)	EKP catch and effort data provided on 21/4/2020	Fisher data were encrypted. Post-extract processing was undertaken in MS Excel. Daily records were aggregated to Period (month) x Fisher x Reporting Zone during extract, with total Period (monthly) effort estimated from the number of daily records reported for each Fisher x Reporting Zone during that period. For Ocean Prawn Trawl data, catch of other species was matched as described for ComCatch data.
Length-frequency data (01/01/1991–01/02/2020)	Data was collected through the New South Wales Port Monitoring Program, or discrete research projects, and extracted from the Resource Assessment and Monitoring database.	Length data was weighted to corresponding catch levels using in house Pieces software.
Queensland		

Continued on next page

Table A.1 – *Continued from previous page*

Data	Details	Notes
CFISH data extraction	Data provided 6/9/2004; 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).

Appendix B Model inputs

B.1 Harvest

The total catch for each zone within New South Wales and Queensland is provided in Table B.2.

Table B.1: The total catch (in tonnes) per zone used in the analyses of the New South Wales and Queensland EKP fishery

	NSW			QLD		
Year	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 5**	**Zone 6**
1988	310	378	290	364	154	302
1989	475	541	345	898	228	352
1990	548	464	257	879	435	354
1991	491	422	229	843	554	496
1992	425	369	223	954	449	441
1993	325	406	202	748	490	458
1994	381	339	164	722	388	509
1995	283	391	189	885	632	603
1996	309	375	196	925	620	490
1997	253	280	179	926	495	540
1998	328	331	101	984	591	636
1999	304	372	165	903	476	479
2000	386	405	205	587	503	548
2001	399	505	278	834	732	813
2002	344	454	242	689	918	591
2003	367	372	231	835	1142	651
2004	279	269	207	901	824	696
2005	148	177	157	905	703	632
2006	167	199	191	863	591	814
2007	222	227	188	650	661	727
2008	219	192	164	780	686	930
2009	165	212	171	939	1004	890
2010	178	253	175	909	889	1156
2011	174	140	99	651	622	658
2012	233	145	135	877	713	1016
2013	187	229	193	656	915	1253
2014	210	239	140	680	852	1144
2015	260	216	132	703	588	1095
2016	330	244	111	686	588	901

Continued on next page

Table B.1 – *Continued from previous page*

	NSW			QLD		
Year	**South**	**Central**	**North**	**Inshore**	**Offshore south**	**Offshore north**
2017	292	267	118	1165	671	1097
2018	196	226	161	961	583	886
2019	177	240	176	869	566	726

Within each zone different grids were selected for different component of the analysis and data inputs. The selection of grids were based on those included in the previous assessment (Courtney et al. 2014). For the New South Wales catch rate standardization, 5 grids were selected (Table B.2) and for the Queensland catch rate 18 grids were selected (Table B.2). For the analysis of fishing power 14 grids from Queensland were selected, and covered the general movement patterns and geographical distribution of the species.

Table B.2: The total catch (in tonnes) per grid used in the analyses of the New South Wales and Queensland EKP fishery—in the estimate of fishing power 14 grids from Queensland were used and for the catch rate standardization, 5 grids from New South Wales and 18 grids from Queensland were used

Catch rate standardisation	Fishing power	Zone	Locality
Queensland			
18 grids	14 grids	Zone	(within the Queensland Southern offshore trawl region)
U28	U28	zone 6	Offshore north
U29	U29	zone 6	Offshore north
V28	V28	zone 6	Offshore north
V30	V30	zone 6	Offshore north
V31	V31	zone 6	Offshore north
W26	W26	zone 6	Offshore north
W27	W27	zone 6	Offshore north
W28	W28	zone 6	Offshore north
X32		zone 5	Offshore south
X33		zone 5	Offshore south
X34		zone 5	Offshore south
X35	X35	zone 5	Offshore south
X36	X36	zone 5	Offshore south
X37		zone 5	Offshore south
W33	W33	zone 4	Inshore
W34	W34	zone 4	Inshore
W35	W35	zone 4	Inshore
W36	W36	zone 4	Inshore
New South Wales			
1001		zone 3	NSW North
1002		zone 2	NSW Central
1003		zone 1	NSW South
1004		zone 1	NSW South
1005		zone 1	NSW South

B.2 Catch rates

B.2.1 Catch rate standardisation

The linear mixed models included fixed $X\beta$ and random model terms $Z\gamma$, and followed the methods and terminology by O'Neill et al. (2007) and Braccini et al. (2012a). Where data were relevant (X_1, X_2, X_3, X_4, X_5, Z_1, Z_2) and available, the models were fit to estimate the following parameter effects:

- scalar model intercept β_0
- abundance β_1 (fishing year × month × area 3-way interaction),
- vessel gears β_2 (log engine rated power, propeller nozzle, GPS, net type, log net length × zone interaction, log mesh size, ground gear type, otter board type, BRDs and TEDs, and use of try-gear net,
- lunar phase β_3 (for luminance and luminance shifted 1/4 phase) (Queensland only),
- fishing effort β_4 (log hours for Queensland EKP daily catches or log days for New South Wales EKP month catches),
- alternate target species β_5 (log New South Wales school trawl whiting kgs + 0.001),
- vessels γ and
- fishing logbook grids γ_2

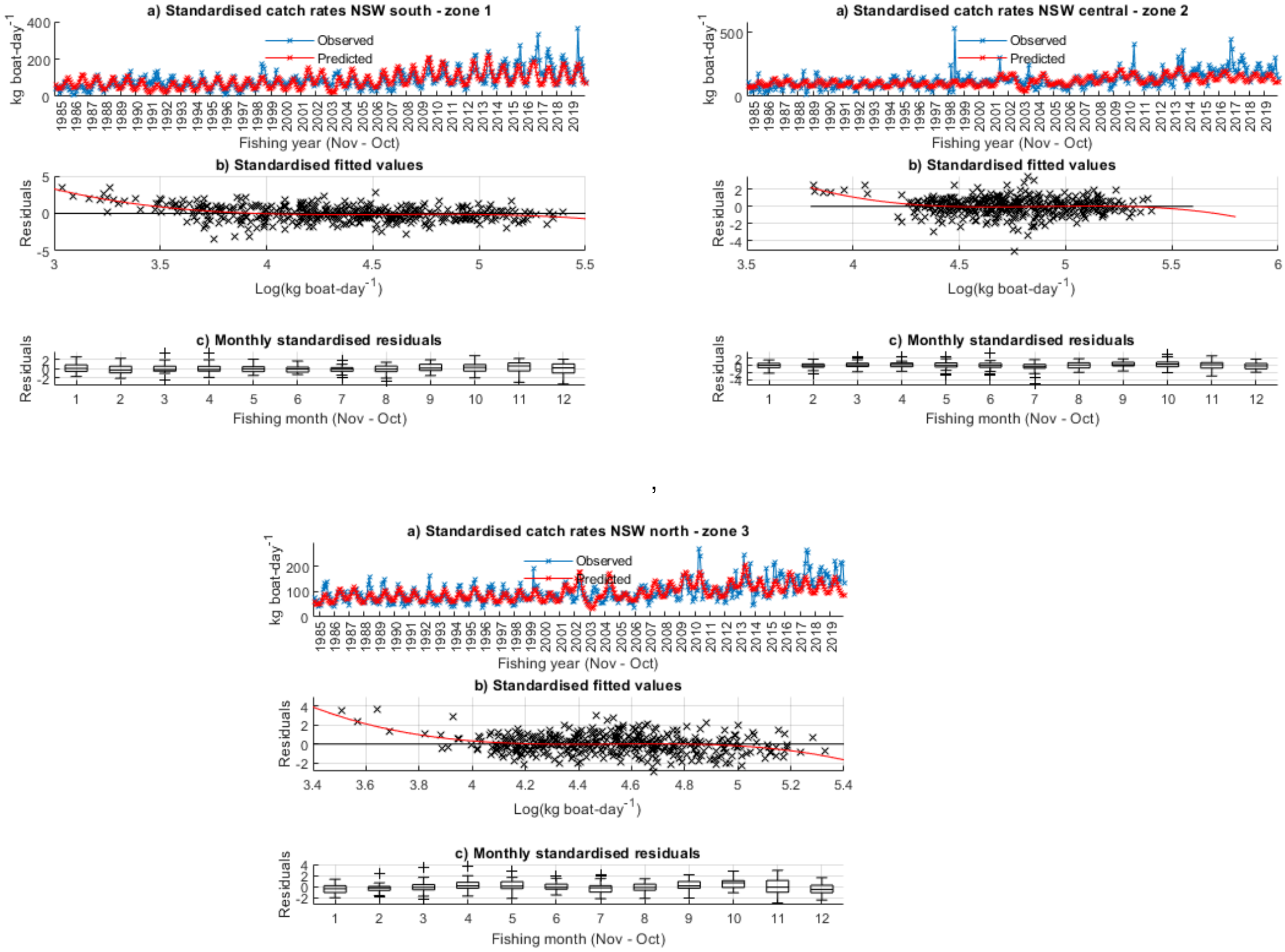

Figure B.1: New South Wales zone 1 to zone 3: diagnostics for observed and predicted standardise catch rates

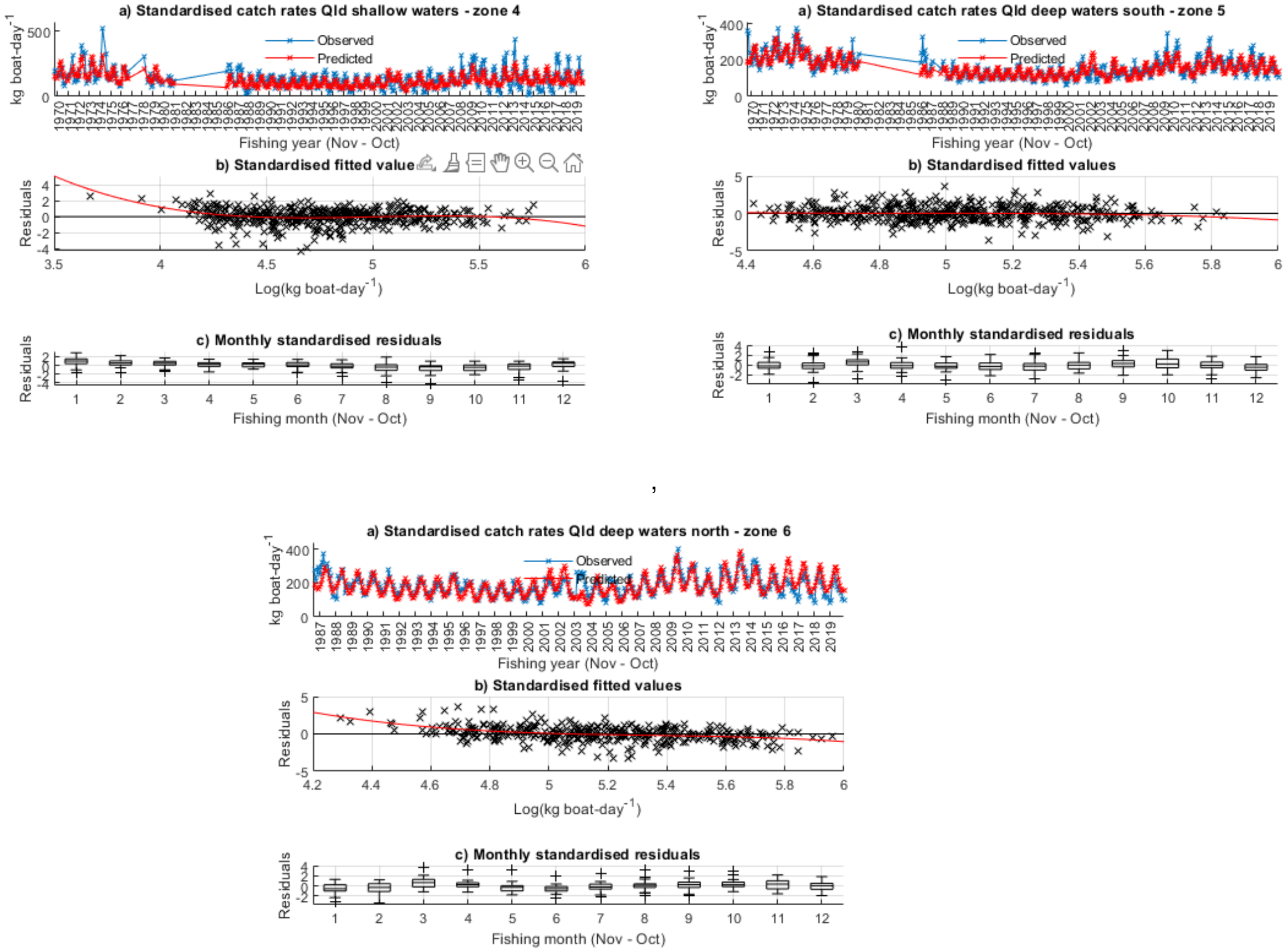

Figure B.2: Queensland zone 4 to zone 6: diagnostics for observed and predicted standardise catch rates

B.2.2 Survey abundance indices

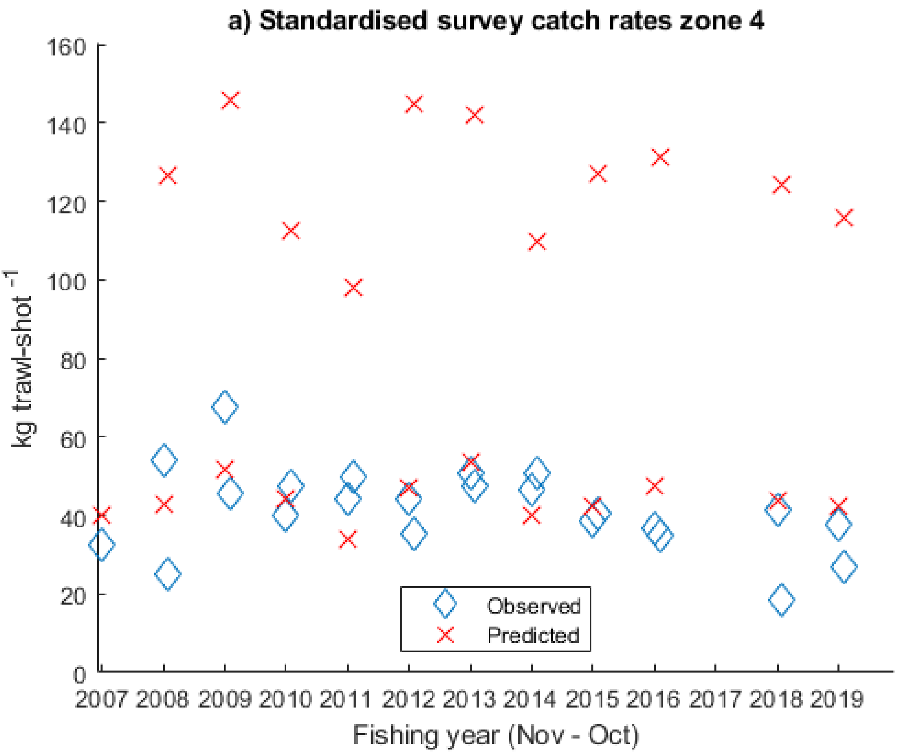

Figure B.3: Abundance estimates from fishery independent beam trawl surveys

B.3 Length frequency

B.3.1 Commercial length frequency

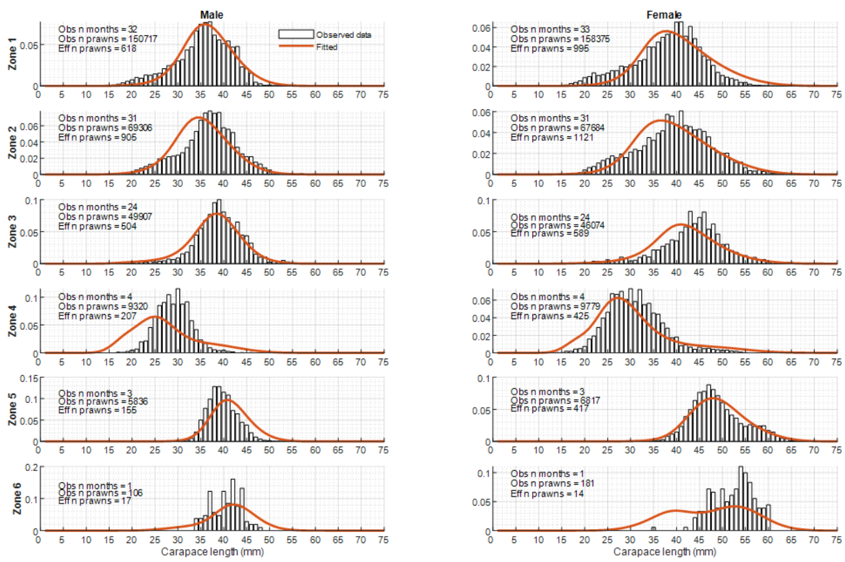

Figure B.4: Length frequency distribution of prawns from New South Wales and Queensland for females and males

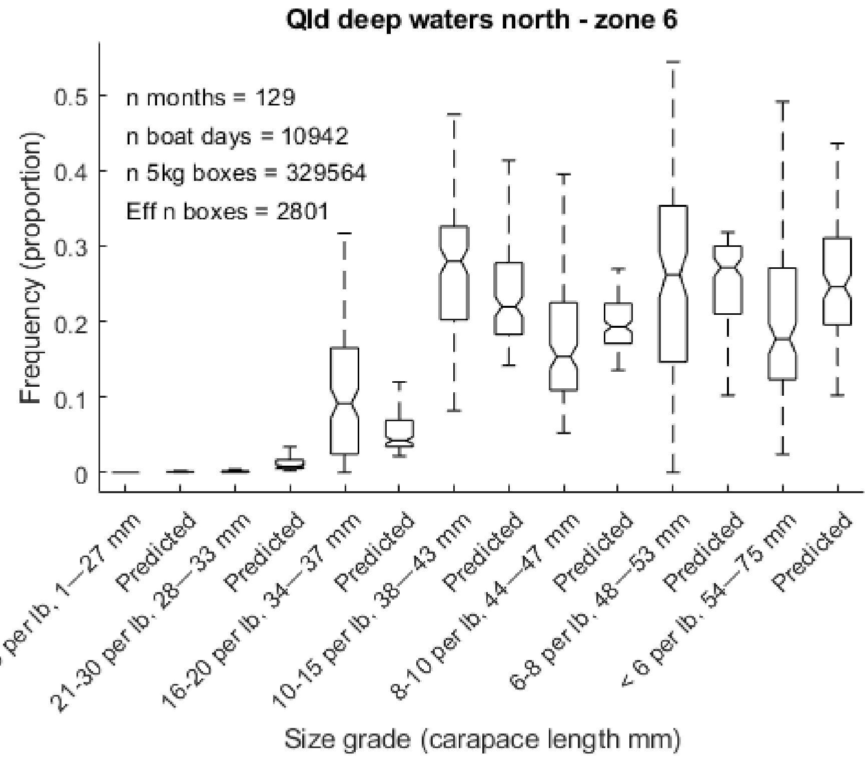

Figure B.5: Summary of grading data—numbers of 5 kg boxes in each size grade from each logbook grid, provided by five vessels over a period of approximately 10 years

B.3.2 Survey length frequency

Beam Trawl Survey data was used to determine the length frequency required to recruit prawns into the model.

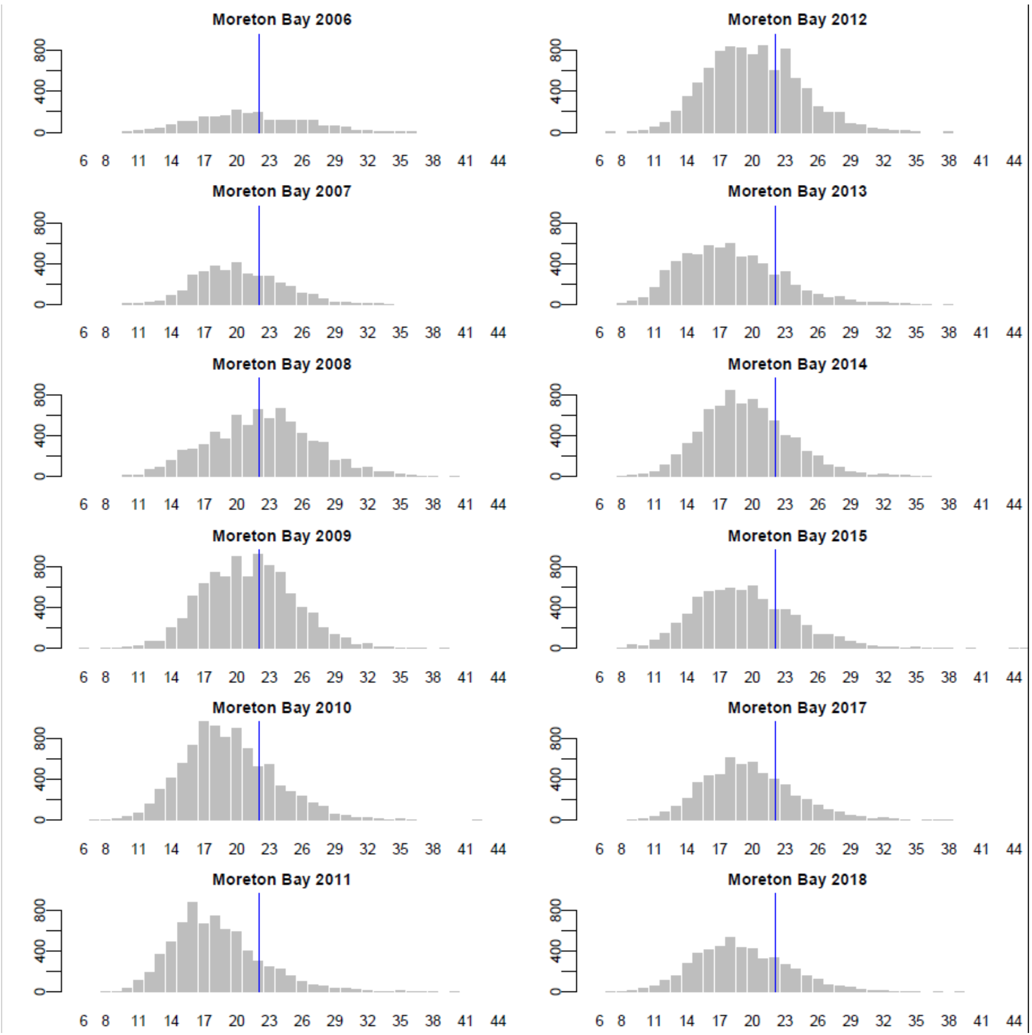

Figure B.6: Length frequency distribution of prawns between 0–40 mm carapace length

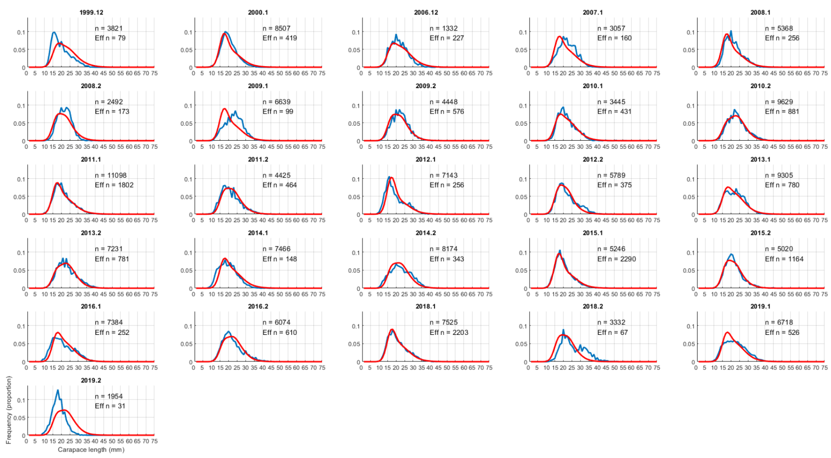

Figure B.7: Length frequency distribution from fishery independent beam trawl survey for females and males

B.4 Pre-recruits

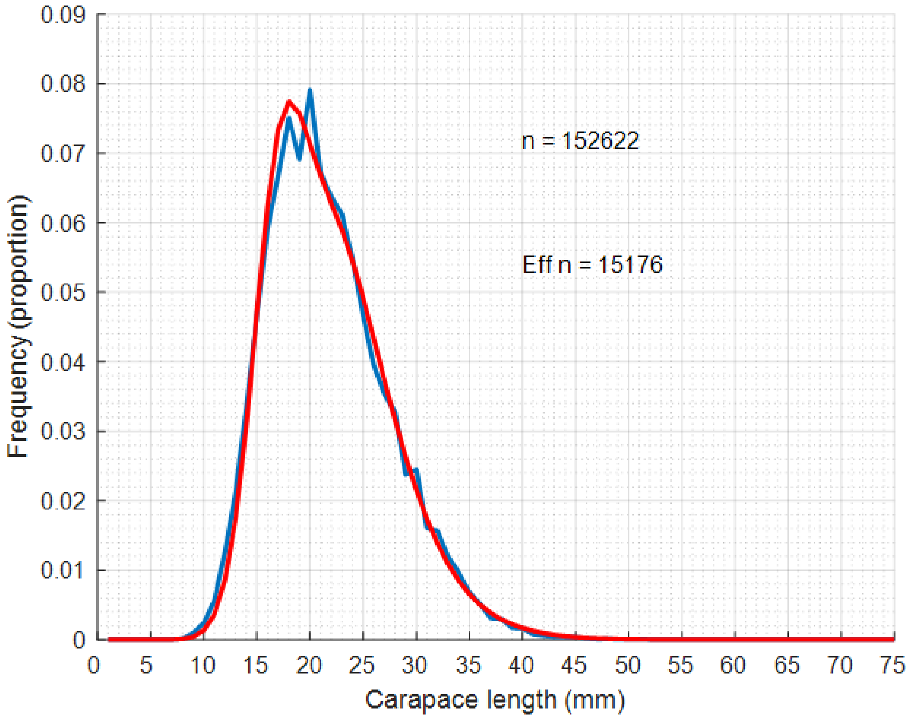

Figure B.8: Final length frequency distribution used to recruit prawns into the model

Appendix C   Model outputs

C.1   Catchability and selectivity

The catchability and selectivity applied to each zone within the model

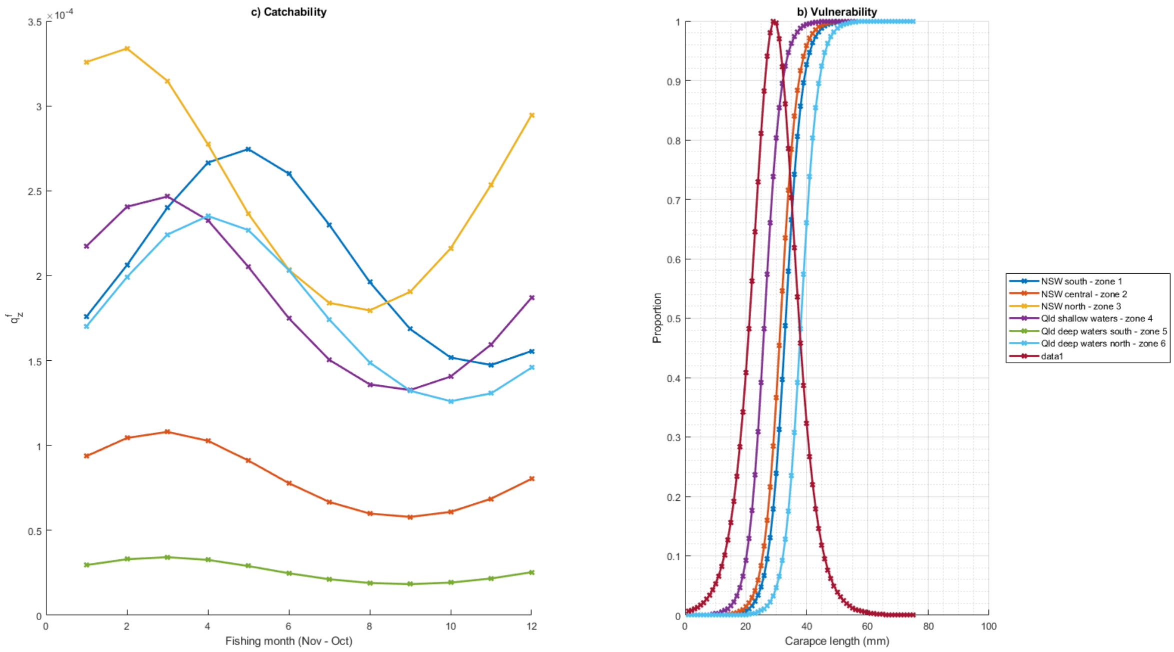

Figure C.1: Catchability and selectivity

C.2   Stock recruitment

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

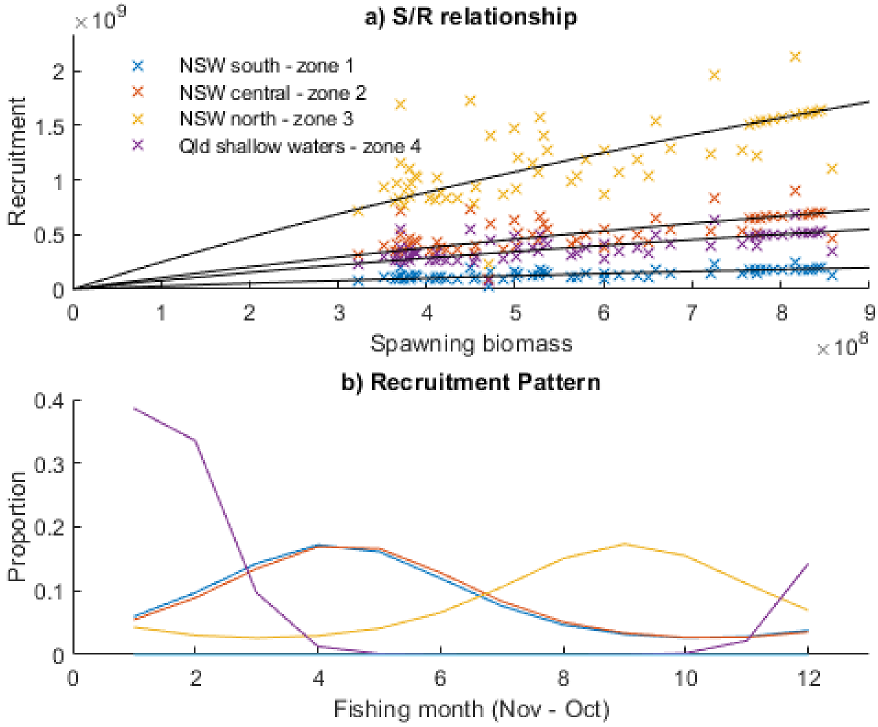

Figure C.2: Stock recruitment relationship

C.3 Recruitment

The model predicted a stable recruitment pattern prior to the year 2000 and thereafter strong fluctuations were evident with years of higher than average recruitment in 2001, 2003 and 2012 (Figure C.3).

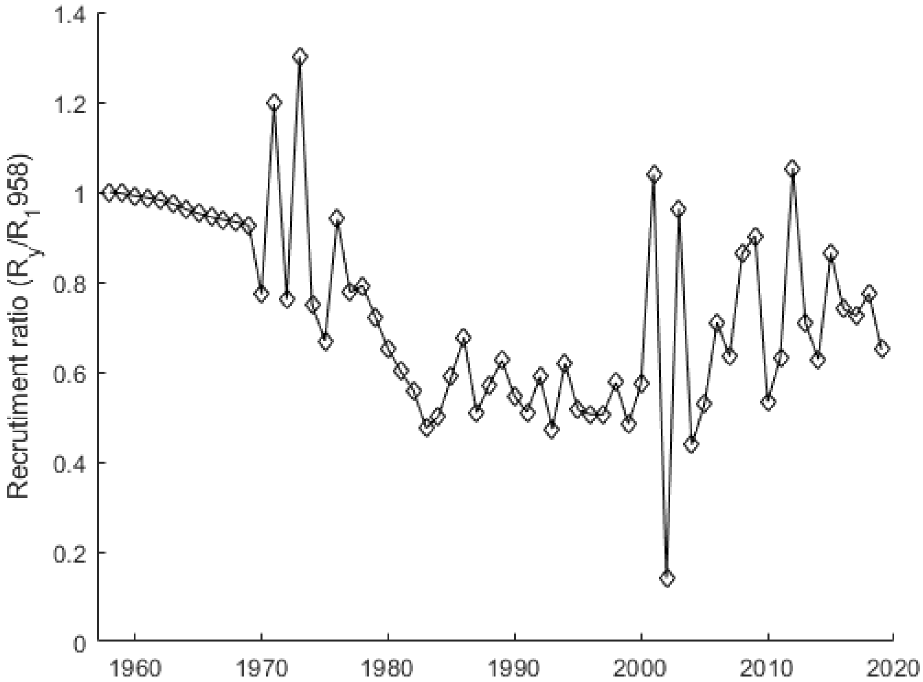

Figure C.3: Recruitment ratio estimated by the model

C.4 Phase plot

The annual condition of the stock relative to the fishing pressure for each year shows the trajectory over time of fishing pressure verses spawning biomass ratio (Figure C.4). Fisheries Queensland aims to maintain stock at a spawning biomass at 60%. The population model calculates the harvest rate required to maintain the biomass at various levels. This harvest rate (or fishing mortality), required to maintain the stock at 60% biomass is denoted F_{60} (as shown on the phase plot). Currently the stock is being fished at a fishing intensity that is appropriate for maintain it at 60% biomass.

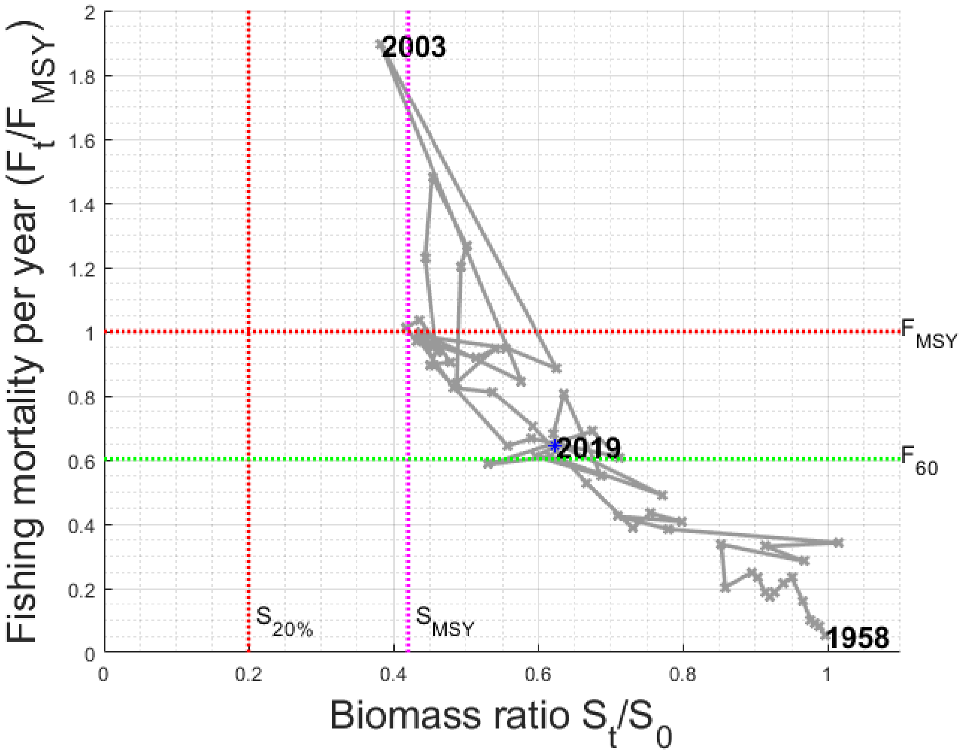

Figure C.4: Annual fishing pressure relative to the predicted spawning biomass trajectory

Appendix D Harvest targets

Table D.1: Description of current performance indicators and reference points for 2019 assessment with confidence intervals (CI)

	MSY	Harvest at 60%	MEY	E_{MSY}	E_{60}	E_{MEY}	MSY ratio	target ratio	MEY ratio	harvest 2019	harvest last5y
Median	2423	2155	1786	27242	16450	11423	0.42	0.6	0.7	2738	3023
Lower CI	2233	1984	1644	18535	11063	9753	0.41	0.6	0.64	2738	2738
Upper CI	2607	2324	1972	33020	20008	12339	0.42	0.6	0.74	2738	3582