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Stock assessment of the Joseph Bonaparte Gulf Redleg Banana Prawn (*Penaeus indicus*) Fishery to 2023, with TAE Recommendations for 2024

Final Report

AFMA Project No. 2020/0833

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Version	Updates	Approver
Version 1	Draft Final Report	AFMA
Version 2	Final Report	AFMA

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Acronyms

AAV	Average Annual Variability
AFMA	Australian Fisheries Management Authority
BOM	Bureau of Meteorology
CPUE	Catch Per Unit Effort
CSIRO	Commonwealth Scientific and Industrial Research Organisation
HCR	Harvest Control Rule
HS	Harvest Strategy
MEY	Maximum Economic Yield
MSE	Management Strategy Evaluation
MSY	Maximum Sustainable Yield
NPF	Northern Prawn Fishery
NPFI	Northern Prawn Fishery Industry
NPRAG	Northern Prawn Fisheries Resource Assessment Group
OM	Operating Model
SOI	Southern Oscillation Index
RAG	Resource Assessment Group
SFR	Statutory Fishing Right

Executive Summary

The assessment model for Redleg Banana Prawns (*Penaeus indicus*) utilising the additional data available for 2023 was updated. In this integrated model, quarterly time steps are used to represent the stock and fishery dynamics. The model is fitted to available catch and effort data. We standardised effort data by applying the updated fishing power series derived for Redleg Banana Prawns. With the model, we calculated a 2024 Total Allowable Effort (TAE) recommendation for Redleg Banana Prawn sub-fishery in the Joseph Bonaparte Gulf (JBG).

In 2023, 86% of the fishing effort and 82% (254t) of the catch was in the JBG area, with the balance taken from Colville-Melville (CM) and none from Fog Bay (FB); total catch across all areas was 309t. Effort in JBG 2023 was 212 boat days; total effort across all areas were 246 boat days. Previously, most of the fishing effort was distributed in the second and third quarters (Apr-Sept), but given the harvest strategy change implemented in 2021 to permanently close the first season to Redleg Banana Prawn fishing, all of the 2023 fishing effort was in the second season.

The 2023 JBG effort exceeded the data-sufficient number of 70 boat days, hence a stock assessment is conducted using the 2023 data updates. The number of boat days in the 4th quarter was 20 days, hence (marginally) at the cut-off required for using the CPUE in the stock assessment. The 2023 nominal CPUE observation for the third quarter was larger than the average (since the 2000s) and for the fourth quarter approximately average. The fishing power was estimated to have decreased 5% in 2023 relative to 2022.

The stock assessment suggests an increase in the stock to around 117% of the BMSY level, with the 2023 Spawning Biomass (3508t) estimated to be at the target BMEY level. Variability about BMSY is to be expected for a variable stock, but it is encouraging that the stock appears to have recovered rapidly over the past three years. This is consistent with the reduction in fishing effort and also expected change under the revised HS as closing the first season was predicted to allow the stock to recover rapidly.

The Reference Case recommended TAE for 2024, under the new strategy of fishing only in the second season, is 412 boat days (90% confidence interval [300;524]), with a

corresponding catch prediction of 683 [351;768] tonnes (Table 1). The predicted catch and effort are based on assuming the same future fishing pattern as used in last year's assessment, noting this may be revised once more data are available to inform on the relative effort in the third and fourth quarters.

The updated stock assessment model (which includes estimation of the 2023 stock-recruitment residual) estimates that the 2023 fishing mortality was 60% of the target level and hence that overfishing was not occurring.

Table 1. The change in nominal effort and catch over a two-year period (2023 observed versus 2023 model predicted) for the redleg banana prawn fishery in the JBG.

Factor (effort or catch)	Value	% difference from 2023
Effort 2023 – boat days	212	
Predicted effort 2024 – boat days (i.e. Recommended TAE)	412	+94
Catch 2023 - tonnes	254	
Predicted Catch 2024 - tonnes	683	+169

Acknowledgements

This project benefitted from consultation with, and extensive feedback from, members of the Northern Prawn Fisheries Resource Assessment Group (NPRAG). Australian Fisheries Management Authority (AFMA) and the Northern Prawn Fishery Industry (NPFI, Ltd.) are acknowledged for providing the data required for this project, and financial support was provided by AFMA and the CSIRO Environment. We thank Laura Blamey and Rob Kenyon for constructive comments on an earlier version of the report.

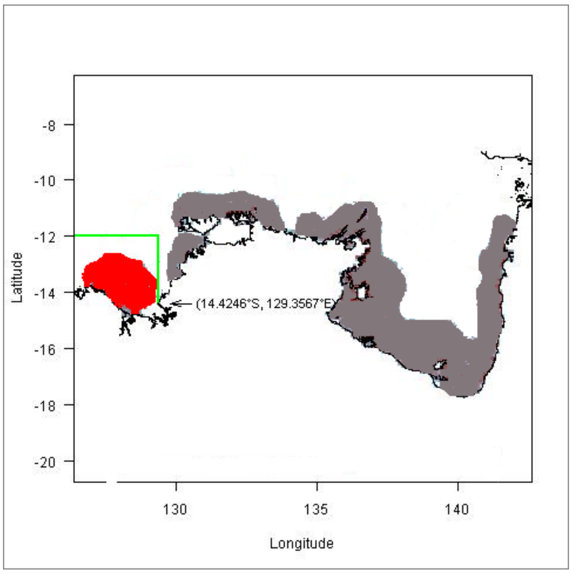
1 Background

The Northern Prawn Fishery (NPF), which commenced in the late 1960s, extends from Cape Londonderry in Western Australia to Cape York in Queensland (Gillett 2008). In some years it is the most valuable Commonwealth-managed fishery. The NPF targets at least nine species of prawns, the main species being White and Redleg Banana Prawns (*Penaeus merguiensis* and *P. indicus*), two Tiger Prawn species (*Penaeus semisulcatus*, *P. esculentus*) and two Endeavour Prawn species (*Metapenaeus endeavouri, M. ensis*). Commensurate with the data and available biological information, a suite of assessment methods have been applied to these species. They range from relatively simple biomass dynamic models (Zhou et al. 2023), through delay-difference models (Dichmont et al. 2003) to size-structured population dynamics model (Punt et al. 2010). A bio-economic model is used in the Tiger Prawn fishery, to predict catch and effort levels maximising net present value (Punt et al. 2011). For the Redleg Banana Prawn fishery of the Joseph Bonaparte Gulf (JBG), we apply an integrated model that represents dynamics on a quarterly time step.

Although fished extensively through southern Asia to East Africa, Redleg Banana Prawns are a relatively small percentage of the total NPF prawn catch (between 2011 -2020, *P. indicus* were 4-17% of the total Banana Prawn catch). Most *P. indicus* within the NPF are caught in the Joseph Bonaparte Gulf (JBG). A Redleg Banana Prawn area (Figure 1), comprising the main fishing grounds where Redleg Banana Prawns are caught in the JBG, has been defined for management purposes.

The *P. indicus* fishery essentially developed in the early 1980s. The fishing grounds are in deeper waters than is the case for *P. merguiensis* (White Banana Prawns) and fishing takes place both day and night. Fishing centres on neap tides, as JBG has large tidal flows (tidal range is up to 7m) (Plagányi et al. 2020).

Figure 1. The area defined as the JBG fishery for Redleg Banana Prawns. Boundaries were recommended by NPRAG and incorporated in the NPF Harvest Strategy. This figure is adapted from Dichmont et al. (2010, Figure 4). Figure production compliments of W.M. Venables (CSIRO) *pers. comm*.



Substantial changes in fishing effort in the JBG fishery saw the number of days fished increase through the 1980s and 1990s, to a peak of about 2,471 boat days in 1997, but then falling to lows of just 161 and 149 boat days in 2008 and 2012, respectively. The lowest effort years were recorded in 2015, 2016 and 2019. The JB effort in 2023 was relatively low at 212 days.

Changes in effort over the entire period of the fishery reflect not only prawn catch rates but also historical management changes. These included large reductions in the number of vessels able to participate in the fishery and the introduction of seasonal closures (further detail is provided below). Inter-annual changes also reflect the response of operators to fluctuating catch rates, prices and values in other parts of the fishery (Pascoe et al. 2020), and more recently the role of environmental variability has also been explicitly recognized (Plagányi et al. 2021).

To account for the potential effects of environmental variability and extremes, Blamey et al. (2020, 2021) applied a management strategy evaluation (MSE) approach to test the robustness of the redleg banana prawn harvest control rules to environmental variability. The MSE testing resulted in a plausible subset of management alternatives, and stakeholders selected a permanent closure of the first fishing season based on overall performance of this option; ability to reduce the risk of fishery closure and stock collapse; robustness to uncertainties; and ease of implementation (Blamey et al. 2020, 2021).

There are several implications for the harvest strategy and stock assessment arising from closure of the first fishing season, and these are discussed further in Plagányi et al. (2022). The redleg banana prawn assessment relies on standardised CPUE data to serve as an index of stock abundance. In the first instance, closing the first season means that there will no longer be data available for the first season to fit the model to, and hence the model will rely on data obtained from the second season only. Moreover, in closure years or data-insufficient years when the fishing effort falls below 70 boat days, it won’t be possible to reliably update the assessment model.

2 Needs

Based on a set of short-lived, highly-variable species, management of the NPF requires detailed assessments to ensure maximal benefit. Specifically, under the Commonwealth Fisheries Harvest Strategy Policy, there is a need to set Total Allowable Effort (TAE) for Redleg Banana Prawns. Assessment is a core element of the Harvest Strategy for the fishery. Without regular, critical updates the Harvest Strategy would need considerable change and might be ineffectual.

This project is part of the on-going assessment program for the NPF, an integral part of the management of the fishery since the 1980s. The Harvest Strategy (HS) provides harvest control rules (simply, ‘harvest strategies’) for two main species of Tiger Prawns, Blue Endeavour Prawns and Redleg Banana Prawns. There are separate assessments for these prawns.

The assessment of the Redleg Banana Prawn fishery, requires:

1. Standardisation of effort, including an annual update to the fishing power analysis; and

2. Splitting of logbook species group catch data into species.

The Redleg Banana Prawn fishery models will provide TAEs and predicted corresponding catches, and thus make available all the information required for management. Furthermore, the continuous update to the harvest control rules for Redleg Banana Prawns given the recent evidence pointing to recent climate drivers which will need to be considered on an annual basis. This must be also undertaken to meet the requirements of the governments’ revised Harvest Strategy Guidelines, and this assessment supports that research and policy changes.

3 Objectives

The objectives as specified in the original proposal are:

1. Update the fishing power series incorporating data from gear surveys, annually (i.e. in this report 2023 for the preceding fishing years) for the Redleg Banana Prawn fishery;

2. Assess stock status of the Redleg Banana Prawn fishery (and relevant key environmental factors) and provide a TAE for Redleg Banana Prawns for 2024.

4 Method

The analyses presented in this report are based on those of Plagányi et al. (2010, 2022) and subsequent updates and the full details of the assessment model are given in Appendix 1, while Appendix 2 summarises key biological information. The methodology to estimate fishing power of the NPF fleet in the JBG fishery is described in Upston et al. (2020) and Parker et al. (2023) and an updated timeseries is provided for the period 1981-2023. The data rules used in the current assessment are summarized in Appendix 3. Given recent strong environmental anomalies and indications that the stock is influenced by a combination of environmental drivers, a summary of recent key environmental indicators is given in Appendix 4 (see Plagányi et al. 2021 for further details). The stock assessment described in this report was conducted using recent changes implemented as part of the Redleg Banana Prawn Stock Assessment Revision Project (Plagányi et al. 2022a,b) which was necessary to take account of changes to the Harvest Strategy as described in Blamey et al. (2020).

4.1 Catch, Effort and Biological Information

The JBG data were analysed per quarter, the four quarters being defined as those of a calendar year, i.e. Quarter 1 = January – March; 2 = April – June; 3 = July – September and 4 = October – December. A historical catch and effort series for each quarter, for the JBG sector only, from 1980 to 2023 was constructed using all available logbook information (Figure 2). Although sporadic catches were recorded in the area since the 1970s, the JBG prawn fishery essentially developed in the early 1980s. Catches peaked at around 977t in 1997 but decreased to around 131t in 2007. Catches have been variable in subsequent years but the 2014 JBG banana prawn catch of 825.1t (including 819.5t of *P. indicus*) was the second highest annual catch in the history of the JBG fishery (Figure 2a). Catches then decreased substantially in 2015-2016, recovered during 2017-2018 but the 2019 catch was again anomalously low at 47t (Table 2). The 2021 catch was 479t whereas the 2022 catch increased to 622t, but decreased again to 254t in 2023 (Figure 2a). Seasonal catches in the fishery strongly reflect fishing effort patterns (Figure 2).

First quarter catches in JBG have never been substantial. JBG was fished in the first quarter in the early 1980s but catches and effort were small. Effort focused on the third and fourth quarters during the early years of the fishery. With the introduction of the seasonal closure from 1987, the first quarter was closed to fishing. Historically the larger catches during the year were from second quarter and from the mid-1980s, this quarter (now beginning the first season of the NPF) increased in importance. However, to address apparent reduced recruitment in JBG, this quarter was also subject to seasonal closure from 2007-2010. Following the removal of that closure in 2011, and with other fishery operational effects such as effort being directed to high abundances of White Banana Prawns elsewhere in the fishery, the annual pattern of catches over 2011-2020 has differed from the prior period, and changed again since 2021 in response to the permanent closure of the first season to fishing Redleg Banana Prawns (Figure 2b). We accounted for this most recent change by adding a further (fifth) selectivity vector to the model for the period 2021 and subsequent assessments.

Figure 2. **(top) Relative spread of fishing effort through the year, 2011-2023; and (bottom) catch for Redleg Banana Prawns (*Penaeus indicus*) in the Joseph Bonaparte Gulf, shown per quarter for the period 2011-2023.**

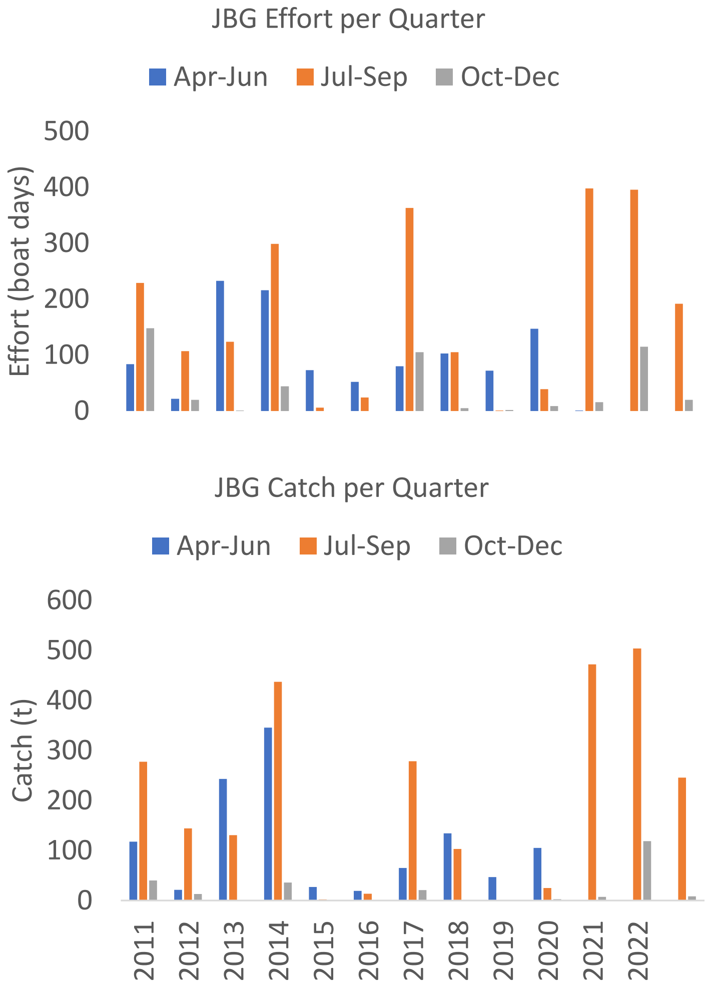


Table 2 Summary of the recent Redleg Banana Prawn catch (tonnes) for Joseph Bonaparte Gulf and Total catch

Year	JBG	Total
1981	143.5	148.6
1982	588.6	596.7
1983	547.4	549.6
1984	653.5	666.5
1985	523.3	553.2
1986	657.6	675.1
1987	694.9	722.3
1988	520.6	535.1
1989	525.4	542.7
1990	500.3	519.8
1991	434.9	480.6
1992	193.4	222.0
1993	749.1	795.8
1994	581.1	592.7
1995	739.0	743.8
1996	498.4	527.8
1997	976.6	1126.3
1998	255.9	257.3
1999	590.5	625.1
2000	379.2	392.9
2001	274.2	306.0
2002	405.0	407.9
2003	364.9	376.2
2004	468.7	473.7
2005	299.9	308.1
2006	200.5	209.2
2007	130.9	159.0
2008	162.2	240.1
2009	471.8	510.3
2010	233.2	240.6
2011	435.3	475.2
2012	178.9	190.7
2013	374.3	380.6
2014	819.5	846.8
2015	29.5	55.7
2016	33.1	66.5
2017	364.6	430.2
2018	237.6	247.8
2019	47.3	66.7
2020	133.4	144.5
2021	479.3	502.7
2022	622	652
2023	254	309

The Base Case model uses a standardised CPUE series which accounts for fishing power effects. Figure 3 summarises the fishing power input series for Redleg Banana Prawns. A marginal decrease in relative fishing power is estimated for 2023 (by ~5%) c.f. 2021.

Nominal CPUE for 2023 was above average (where average is computed over the period 2000 to 2022) (Figure 4).

Figure 3. The updated Redleg Banana Prawn relative fishing power series (1981-2023).

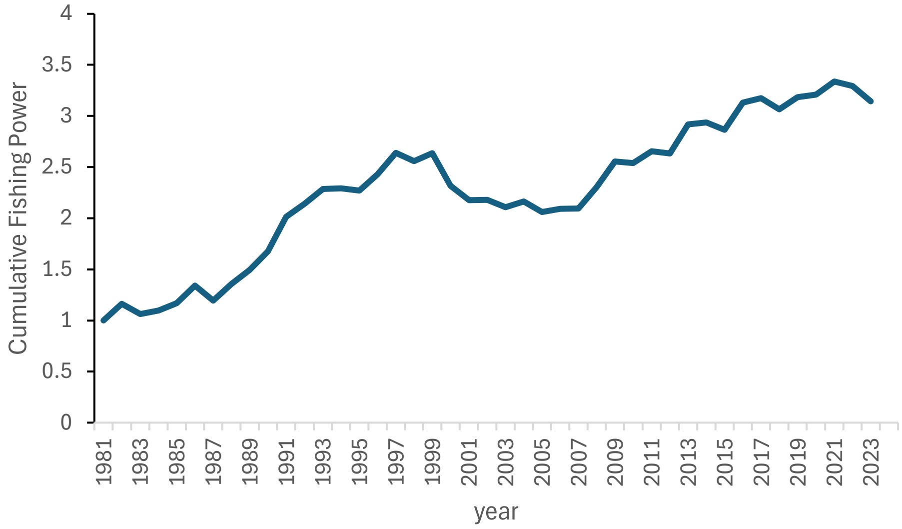
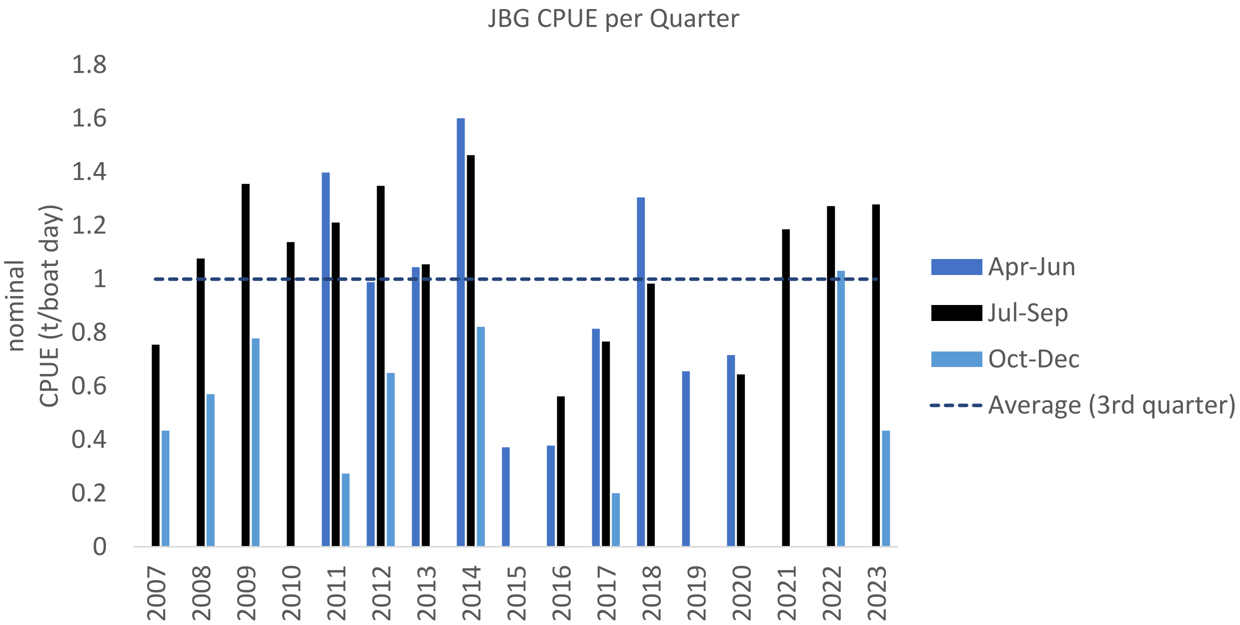


Figure 4. Comparison of the average nominal CPUE over August to October for years 2011 to 2023 with the average (2000-2022) for the third quarter (Jul-Sep) shown as a dashed line.



4.2 Closures in the NPF

A variety of spatial and temporal closures have been implemented over the years in the NPF. Substantial change was implemented in 1987, when an end of year (1 December to March/April) and a mid-year (22 June to 1 August) closure were introduced. The model accounts for the end of year closure by setting relative availability to zero for the first model quarter post-1987, and estimating separate availability parameters for the pre- and post-closure periods. The estimated availability parameters represent the combination of a variety of factors including reduced availability during a 3-month quarter due to partial closures, and fishing selectivity effects such as a proportion of the stock being too small to be fished.

During 2007-2010, the JBG was closed to prawn fishing during the first season (April to June). This corresponds to the second quarter in the model and is accounted for in the Base Case model by estimating a third quarter availability vector for 2007-2010 (discussed below). As the JBG was opened and fished during the first season from 2011-2020, a different availability vector is estimated for these years, and a fifth availability vector added for the period commencing in 2021 due to implementation of a permanent first season closure (Blamey et al. 2021).

5 Results

5.1 Model fits and trajectories

Estimated parameter values are shown in Table 3 and Table 4. Comparisons between the observed and model-predicted CPUE values for each quarter are shown in Figure 5. The model fits to each of the quarters separately, and the fits are generally good, particularly for the most key reference fished quarters 2 and 3. For 2021, there were only adequate data (number of boat days > 20) to fit in quarter 3, whereas for 2022 and 2023 the model is fitted to data from quarters 3 and 4. However, the quarter 4 boat days in 2023 is on the cut-off margin so a sensitivity run is provided to check the effect of excluding the last CPUE value in the model fitting.

Estimates of availability per quarter (Figure 6) reflect the changing patterns of closures. The Base Case model estimates a single set of recruitment residuals associated with recruits that are spawned the previous October, recruiting to the fished population at the start of Quarter 2 (Figure 7). Although lower levels of recruitment are modelled to occur during the other quarters, accounting for the variability associated with just one (the major) of these events in Quarter 2, adequately represents resource dynamics.

Figure 5. Comparisons between the standardised CPUE data for each quarter and model-predicted CPUE values using the Base-Case model. Note that data are not included for the following quarters for which there was minimal fishing: Q4 in 2010, 2013, 2015-16, 2018-2021; Q3 in 2015, 2019.

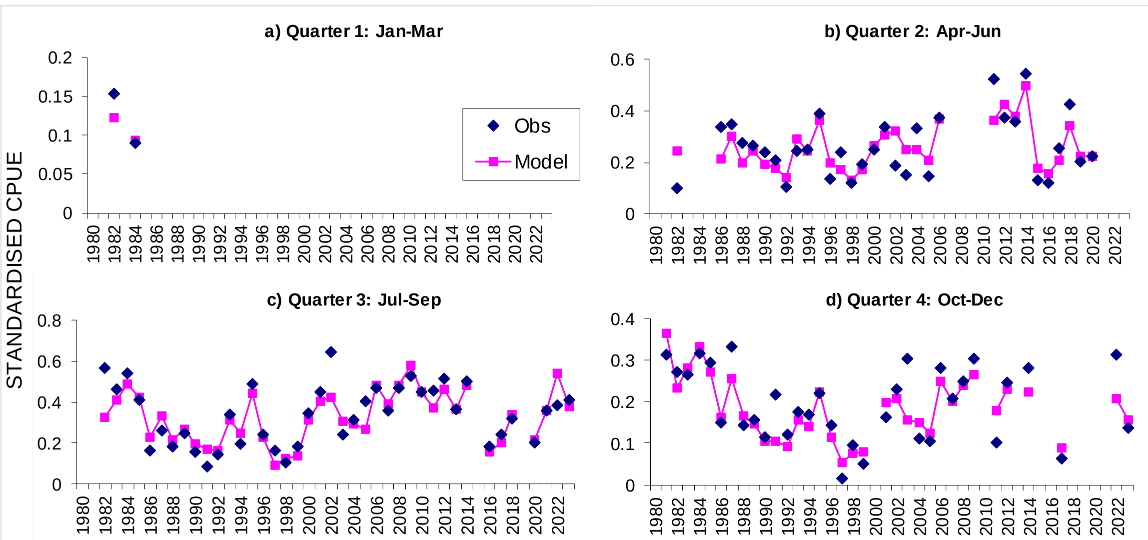


Table 3 Summary of the parameters of the population dynamics model.

Parameter	Treatment
Pre-exploitation equilibrium spawning biomass, K^{sp}_{1980}	Estimate $K^{sp}_{1980,1}$ for first quarter, compute values for other quarters using equilibrium assumptions, and set $K^{sp}_{1980} = \sum_{seas} K^{sp}_{1980,seas}$
Natural mortality, *M*	Fixed at 0.05 wk^{-1}
Recruitment and spawning	
"Steepness", *h*, of the stock-recruitment relationship	Fixed at 0.6
Recruitment residuals , R_s for quarter 2	Estimated – 43 pars for 1981- 2023
Proportion of recruited stock that spawn each quarter, f_s	Assumed known [0.3; 0.05;0.05;0.6]
Stock-recruitment relationship parameters, α, β	Computed using estimated values of K^{sp}_{1980} and *h*
Variance in recruitment, σ_r	Fixed at 0.8 (sensitivities tested)
Fishing mortality related	
Catchability – *q* $(x10^{-4})$	Computed, 2.4e-4
Availability during each quarter for period 1980-1988, $A_{y,s}$	Estimated [1.00 ; 0.64; 0.80; 0.66]
Availability during each quarter for period 1989-2006, $A_{y,s}$	Estimated *(except for pars in italics)* [*0* ; 0.77; 1.00; 0.58]
Availability during each quarter for period from 2007-2010, $A_{y,s}$	Fixed at 1989-2006 estimates for quarters 3-4 [*0 ; 0*; *1.00; 0.57*]
Availability during each quarter for period from 2011-2020, $A_{y,s}$	Estimated *(except for pars in italics)* [0 ; 0.97; 1.00; 0.57]
Availability during each quarter for period from 2021, $A_{y,s}$	Fixed [*0; 0;* 1.00; *0.50*]
Growth parameters	
Von Bertalanffy growth curve parameters	Assumed known
Length-weight regression	Assumed known
The observation model	
Observation error variance, σ	Estimated [0.29]

In the plot of the stock-recruit residuals (Figure 7), the recruits in any quarter correspond to the spawning biomass half a year earlier. Mostly positive residuals for 2006-14, correspond to higher-than-expected catch rates described above (i.e. observed catch rates greater than model estimates). However, the 2015-16 data suggest a period with several lower-than-average recruitment events, followed by a return to above average recruitment (Figure 7). This suggests that environmental drivers or other processes could be impacting on recruitment variability (Plagányi et al. 2021).

Table 4 Summary of (A) Reference Case model parameter estimates and sensitivity analysis with (B) the fishing pattern/selectivity for the fourth quarter since 2021 estimated; (C) estimating separate selectivity for the fishing pattern in 2022; (D) excluding the 4th quarter CPUE estimate for 2023 due to it being based on only 20 boat days and (E) the natural mortality parameter M estimated instead of fixed.

	(A) Reference Case (sigma 0.8)				(B) Sensitivity re Selectivity				(C) Sensitivity - different selectivity (2022)				(D) Sensitivity excluding 2023 4th quarter CPUE				(E) Estimating M			
K_{1980}^{sp}	6706				6468				6439				6811				12203.1			
Steepness *h*	0.6 (fixed)				0.6 (fixed)				0.6 (fixed)				0.6 (fixed)				0.6 (fixed)			
M	0.05 (fixed)				0.05 (fixed)				0.05 (fixed)				0.05 (fixed)				0.034108			
Availability during each quarter for period 1980-1988	1.00	0.64	0.80	0.66	1.00	0.64	0.80	0.66	1.00	0.64	0.80	0.66	1.00	0.64	0.80	0.65	1.00	0.57	0.68	0.58
Availability during each quarter for period 1989-2006	0.00	0.77	1.00	0.57	0.00	0.77	1.00	0.58	0.00	0.77	1.00	0.58	0.00	0.77	1.00	0.57	0.00	0.82	1.00	0.63
Availability during each quarter for period from 2007-2010	0.00	0.00	1.00	0.57	0.00	0.00	1.00	0.58	0.00	0.00	1.00	0.58	0.00	0.00	1.00	0.57	0.00	0.00	1.00	0.63
Availability during each quarter for period 2011-2020	0.00	0.97	1.00	0.57	0.00	0.97	1.00	0.58	0.00	0.97	1.00	0.58	0.00	0.97	1.00	0.57	0.00	1.00	1.00	0.63
Availability during each quarter for period from 2021	0.00	0.00	1.00	0.50	0.00	0.00	1.00	**0.68**	0.00	0.00	1.00	0.50	0.00	0.00	1.00	0.50	0.00	0.00	1.00	0.50
Catchability – *q*	2.4E-04				2.4E-04				2.4E-04				2.4E-04				0.000282			
-lnL:overall	-73.3				-73.8				-75.2				-72.7				-76.37			
Observation error variance	0.29				0.29				0.29				0.29				0.28			
Current depletion - Bsp(2023) relative to B_{MSY}	1.17				1.00				1.13				1.29				1.21			
Current depletion - Bsp(2023) relative to B_{MEY}	0.98				0.84				0.94				1.08				1.01			
Current depletion - Bsp(2023) relative to B_{1980}	0.52				0.45				0.51				0.56				0.28			
F(2023)/Ftarg	0.60				0.74				0.63				0.54				0.91			
No. parameters	53	(43 recruit residuals)			54	(43 recruit residuals)			55	(43 recruit residuals)			53	(43 recruit residuals)			54	ecruit residuals)		
AIC	**-40.522**				-39.555				-40.322				-39.366				-44.7484			

Figure 6. Schematic summary of Base Case model availability vectors for each quarter, for the five periods. a) 1980-1988, b) 1989-2006, c) 2007-2010, d) 2011-2020 and e) from 2021.

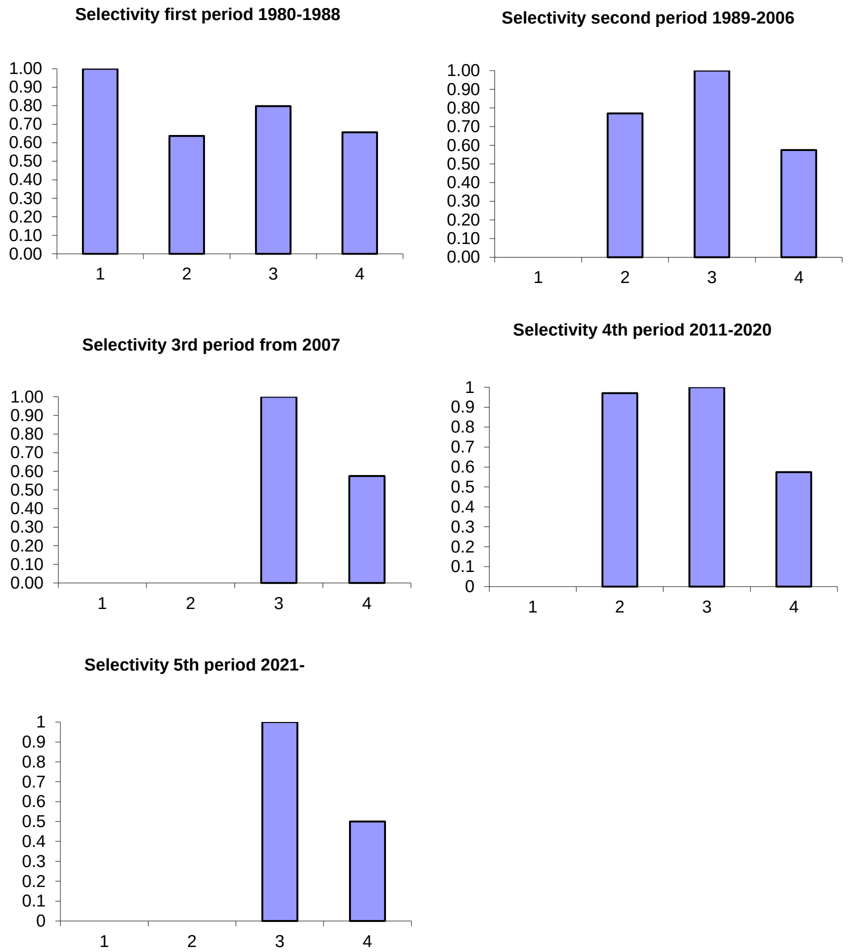
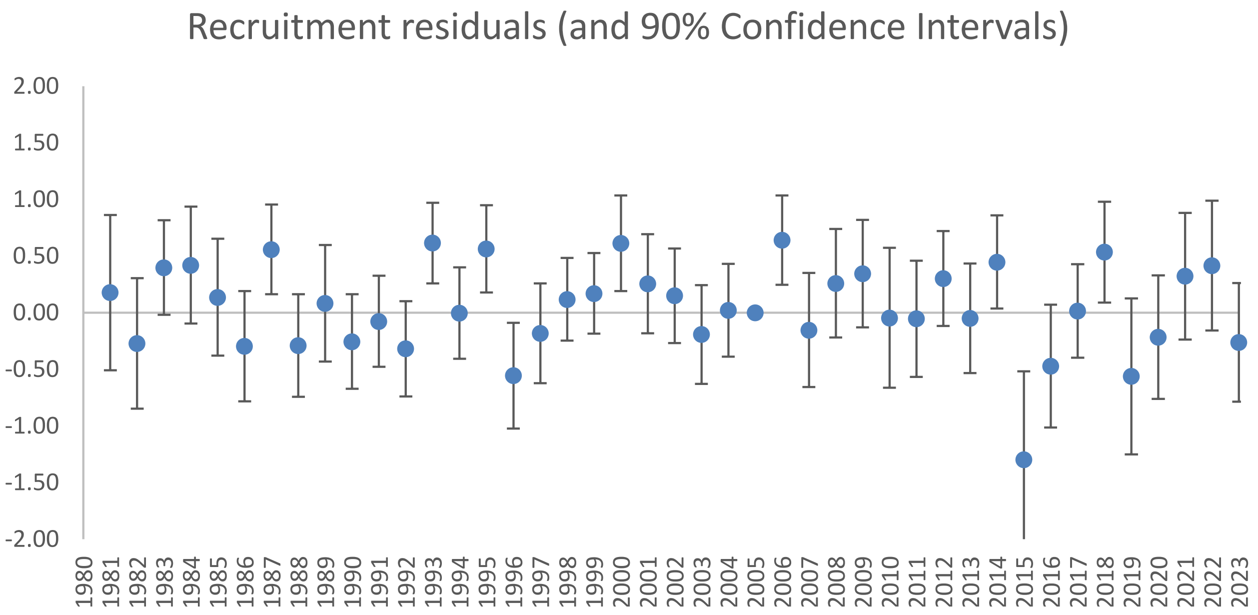


Figure 7. Recruitment estimates for Redleg Banana Prawns in Joseph Bonaparte Gulf, for the Base Case model. Plot shows estimated stock recruit residuals (together with Hessian-based 90% confidence intervals) for the start of the second quarter for all years, 1981-2023.



The total annual spawning biomass trajectory is shown in Figure 8. The prawn population is predicted to have declined after 1995, but to have increased from around 2000 in response to lower catches and good recruitment, but then to have decreased again since 2014 toward the lower limit. However, based on limited CPUE data, the downward trend appears to have reversed briefly in 2018 when it tended back towards the target level, before dipping again below the BMSY level in 2020-2021. However, since 2021 the spawning biomass is estimated to be at or above the BMSY level and in 2023 at the BMEY level. The BMEY, BMSY and BLIM levels are estimated respectively at 3592t, 2993t and 1497t.

The stock size in the last year of the assessment is therefore estimated to be greater than the Biomass Limit Reference Point (BLIM), i.e. B2023 > 0.5 BMSY, with B2023 ca. 2.3 times BLIM. B2023 is estimated to be at 98% BMEY and above BMSY, with relative depletion proportions of 0.98 and 1.17, respectively.

The associated Hessian-based 90% confidence intervals as shown in Figure 9 highlight, nevertheless, the large uncertainty associated with model estimates of spawning biomass. Even considering the associated large uncertainty, there is some confidence that the stock declined substantially over 2015-2017 as evident from the upper confidence limit being below the target level for these years (Figure 9).

Similarly, the commercially available biomass (Bcomm) is predicted to have decreased substantially in 2015-17 to a much lower level than in previous years, but has again increased back to around target levels in recent years (Figure 10).

Figure 8. Total annual spawning biomass (t) trajectory using the Base Case model for 1980 to 2023. The plot also shows the target spawning biomass level (BMEY), the biomass level (BMSY) corresponding to Maximum Sustainable Yield (MSY) and limit reference level (BLIM)

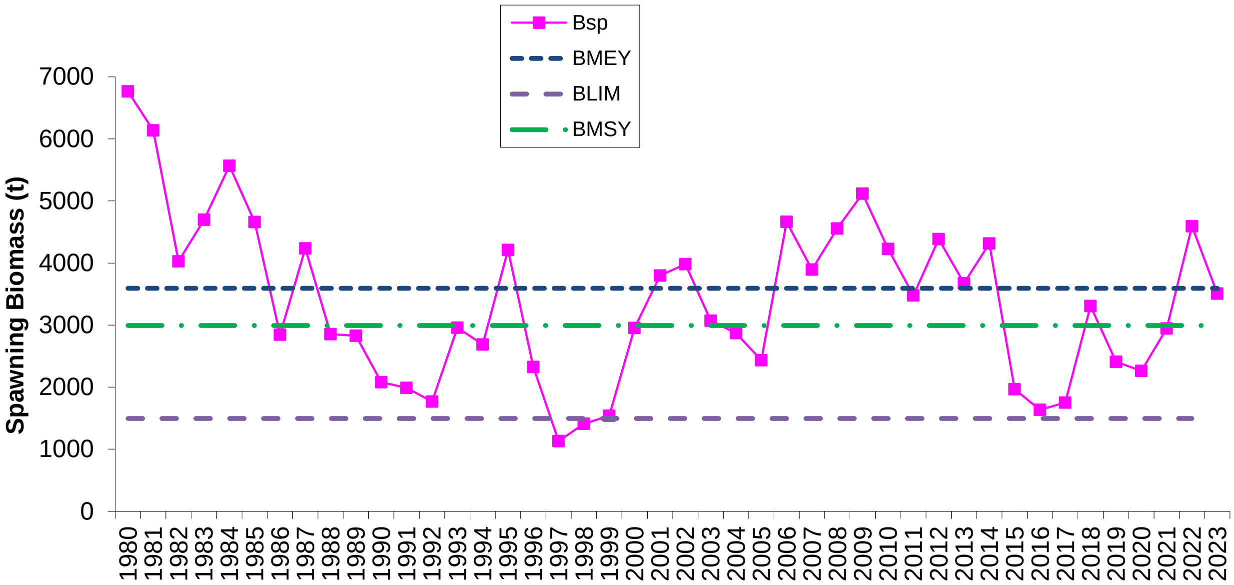


Figure 9. Base Case spawning biomass estimates for the period 1980 to 2023 and projected forward to 2024 (last point shown on right hand side of plot). The shaded areas represent the associated Hessian-based 90% confidence intervals. The biomass is shown relative to model estimates of the biomass level (*BMEY*) corresponding to Maximum Economic Yield (*MEY*), which is used as the target biomass level.

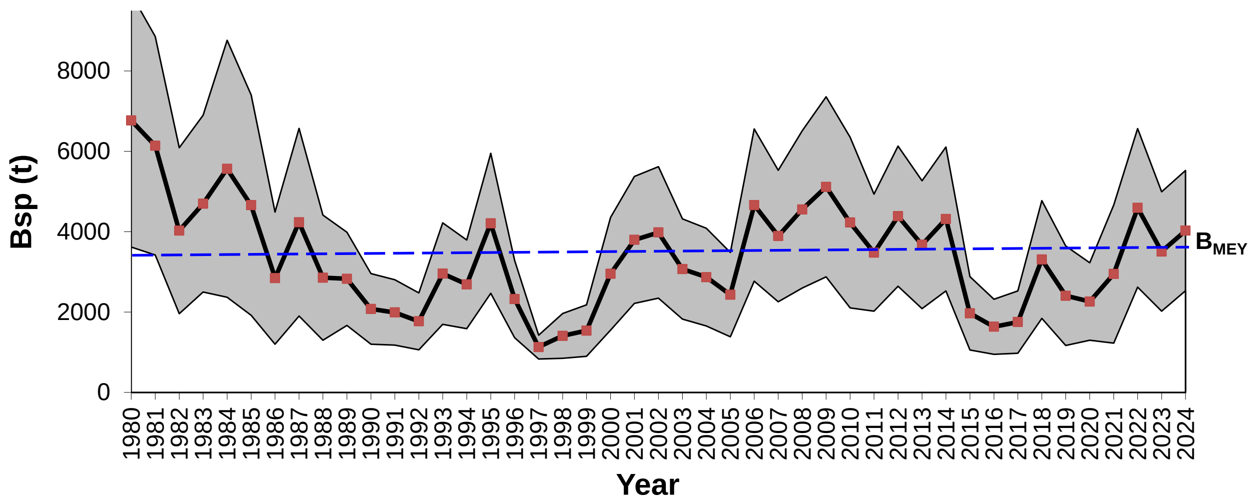
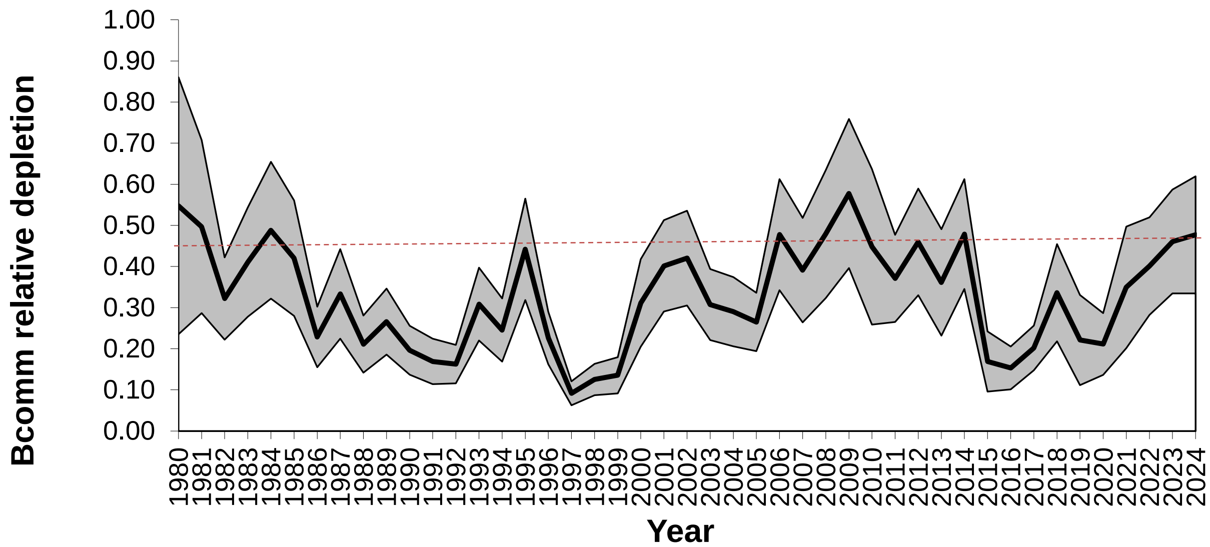


Figure 10. Total commercially available biomass (Bcomm) depletion trajectory using the Base Case model for the period 1980 to 2023, and projected forward to 2024 (last point shown on right hand side of plot). The shaded areas represent the associated Hessian-based 90% confidence intervals



5.2 TAE recommendation for 2024

The Reference Case estimated that the stock is currently at 117% of the BMSY level (Table 5). Applying the revised Hockey-stick control rule (Figure 11), means that the projected fishing mortality proportion should be set at 100% of the target level.

The Reference Case recommended TAE for 2024, with an associated fishing pattern (no fishing in first season) is 412 boat days (90% confidence interval [300;524]), with a corresponding catch prediction of 683 tonnes with wide confidence interval [351;768] tonnes.

The updated stock assessment model (which includes estimation of the 2023 stock-recruitment residual) estimates that the 2023 fishing mortality was 60% of the target level (Table 4) and hence that overfishing was not occurring.

Currently, it is not possible to accurately forward predict recruitment for this highly variable stock, and the actual annual fishing effort is expected to fluctuate about the model derived TAE. Thus, the stock assessment is used to track stock status and the first season closure is the management mechanism used to reduce risk to the Redleg Banana Prawn sub-fishery (Plagányi et al. 2023).

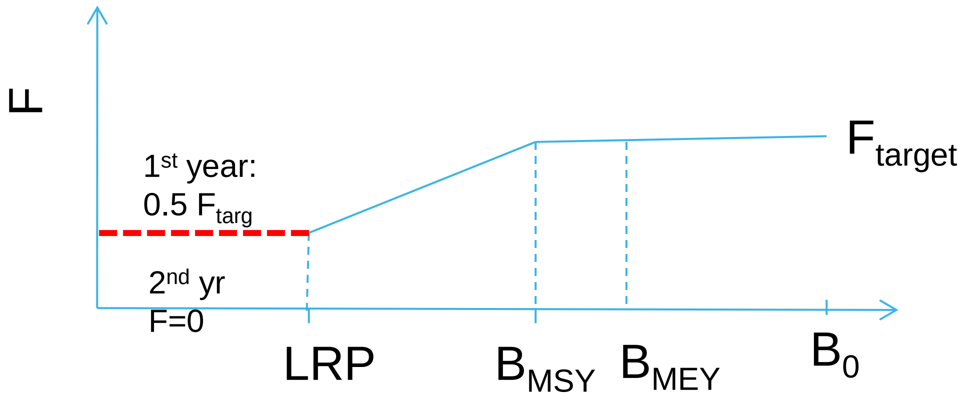
The model TAE for 2024 assumes that, as per 2023, fishing will still occur in the fourth quarter, with the boat days per quarters 3 and 4 being 346 and 66 respectively. The corresponding catch predicted for 2024 is 683t, which is as expected given that the stock is estimated to be roughly at the BMEY level and also that the closure of the first season allows animals time to grow. The first season closure also acts as an additional precautionary buffer against stock depletion (Blamey et al. 2022, Plagányi et al. 2022).

We note also that effort in this fishery depends not only on stock abundance and fleet capacity, but also the response of operators to fluctuating catch rates, prices and values in other parts of the fishery (Pascoe et al. 2020). Hence it is uncertain whether actual 2024 effort will be as high as the TAE. A holistic understanding of how effort is distributed across the entire fishery under different biological, environmental and economic conditions may improve predictions.

As has been discussed in the past, the Redleg sub-fishery is naturally highly variable which means that it is difficult to reliably forward predict stock abundance, although previous work has identified key environmental drivers that likely signal very good or very bad catch years (Plagányi et al. 2021). The 2023 (pre-season) TAE was 689 [502;876] boat days which was substantially higher than the 2023 observed effort of 212 days, with the latter below the predicted 90% confidence interval (502 days). The 2023 (pre-season) catch prediction was 952t with lower confidence interval of 585t, which was high compared to the actual 2023 catch of 254t. Hence in 2023, the fishing effort was only 31% of the available level, and it is therefore not surprising that the catch was 27% of the expected catch.

The updated stock assessment model (which includes estimation of the 2023 stock-recruitment residual) estimates that the 2023 (3rd quarter) fishing mortality was 60% of the target level (Table 4) and hence that overfishing was not occurring.

Figure 11. Summary of revised Hockey-Stick Rule applied to outcomes of the stock assessment.



5.3 Model predictions and sensitivity analyses

Several sensitivity analyses were considered as part of the MSE project (Blamey et al. 2020, 2021) and the Redleg Banana Prawn stock assessment revision project (Plagányi et al. 2021). In Table 4 we present results of selected key sensitivity tests only -the results of the other standard sensitivity tests and diagnostics were as expected and therefore not presented. The sensitivity tests use the same settings as the Reference Case model, including setting sigma=0.8, unless otherwise specified.

The main difficulty in conducting the current assessment related to the assumption that the fishing pattern (represented using a selectivity parameter for each quarter of the year) for years since 2021 (i.e. since implementation of the revised harvest strategy policy involving closing the first season) was similar. It was expected that with fishing occurring in the second season only, the relative amount of fishing effort in the fourth quarter would remain similar. However, during 2022 and 2023, the tiger prawn fishing season length was voluntarily capped by industry to reduce effort on tiger prawns, noting "*the NPRAG…. took a temporary and precautionary once-off approach to setting effort in the tiger prawn fishery, and recommended a moderate cut in effort (as nominal days) relative to the recent five-year average in the fishery*" (Deng et al. 2022). This influenced to varying degrees the amount of effort directed on the redleg sub-fishery, such that the 2022 quarter 4 fishing effort was higher than in the other years. The model is thus unable to fit closely the CPUE for both 2022 and 2023, and this trade-off means that the model artificially estimates a slightly too large stock biomass in 2022 (Figure 5), with flow-on result that the 2023 stock-recruit residual is estimated to be slightly below average (i.e. this is because the model estimates that there was a larger stock biomass in 2022 than is the case). This was verified by conducting a number of sensitivity analyses including (B) alternative approach for estimating the fishing pattern/selectivity for the fourth quarter since 2021 and (C) estimating separate selectivity for the fishing pattern in 2022. Sensitivity (C) involved estimation of two additional parameters and showed that by improving the fit to the 2022 CPUE, the 2023 estimated recruitment residual is as expected (approximately zero) (Figure 12) whereas the corresponding stock depletion level is similar (94% of BMEY level) but has now corrected the artificial 2022 peak suggested by the base-case model. The AIC for sensitivity (C) is similar to the base-case but the preference was to not over parameterise this relatively simple model given its heavy reliance on CPUE data. Future work may provide greater insights into the relationship between tiger and redleg banana prawn fishing effort which may inform better parameterisation of this aspect in future models. Moreover, once the fishery has settled into the new pattern of fishing (and/or anomalous economic conditions ease), then consideration can be given as to how best to present the current fishing pattern without overly complicating the model.

Sensitivity (D) excluded the 4th quarter CPUE estimate for 2023 due to its being based on only 20 boat days. This resulted in fairly minor changes only (Figure 13).

The Redleg Banana Prawn HS specifies that natural mortality (*M*) should be fixed at 0.05 wk^{-1} based on historical tag-recapture data from field tagging and release experiments (Die et al. 2002). These data suggest fairly high natural mortality of ca. 0.05 wk^{-1} based on use of a size-structured model, with the range of estimates obtained for the non-size-structured models being 0.032 to 0.067 wk^{-1} (Die et al. 2002). The *M* used for the tiger prawn assessment model is set at 0.045 wk^{-1} for both species (Deng et al. 2022). The Die et al. (2002) study represents the best available estimates of *M*, but this aspect is also periodically explored in the stock assessment model particularly as changes in natural mortality may have occurred since this time. Sensitivity (E) therefore involved again estimating *M*, which yielded an estimate of 0.034 wk^{-1} with 90% associated confidence interval [0.028;0.041] (Figure 14). *M* was therefore estimated with good associated precision (and similarly for *K*, noting *h* was fixed). The reason that *M* can be estimated is because the available CPUE data show strong signals of stock decline and recovery over the modelled period. The estimate is significantly lower than the fixed input value of 0.05, i.e. the upper 90% (and 95%) confidence limit of the estimate is lower than the model input value of 0.05, but the estimate falls within the range of Die et al. (2002), which suggests that this aspect might be worth investigating further in future work. As expected, a lower *M* estimate corresponds to a much higher estimate of *K* and therefore the stock is estimated to be more depleted relative to the starting spawning biomass than for the Reference Case model (Table 4) but as previously explained, the 1980 starting biomass estimate cannot be considered reliable on its own, especially given the high natural variability of the stock and the limited data to fit the model to for the early years – for example, the average of the first five (or ten) years' spawning biomass would be a more reasonable estimate of B0 and would suggest current depletion is 0.44 (or 0.57) B0. It is thus more relevant to compare stock status relative to the (recalibrated) BMEY and BMSY reference levels, and these are encouragingly similar to the Reference Case (Table 4). However, this sensitivity scenario does suggest a fairly large difference in the TAE, namely 267 [100;435] versus 412 boat days with corresponding catch estimate of 346t versus 683t. This model version was the preferred model based on the AIC criterion, but further work is needed before there is a sufficiently strong basis for deviating from the field estimate of *M* as prescribed for use in the Harvest Strategy.

Figure 12. Selected results from sensitivity test (C), which involved estimation of two additional parameters related to fishing pattern and selectivity.

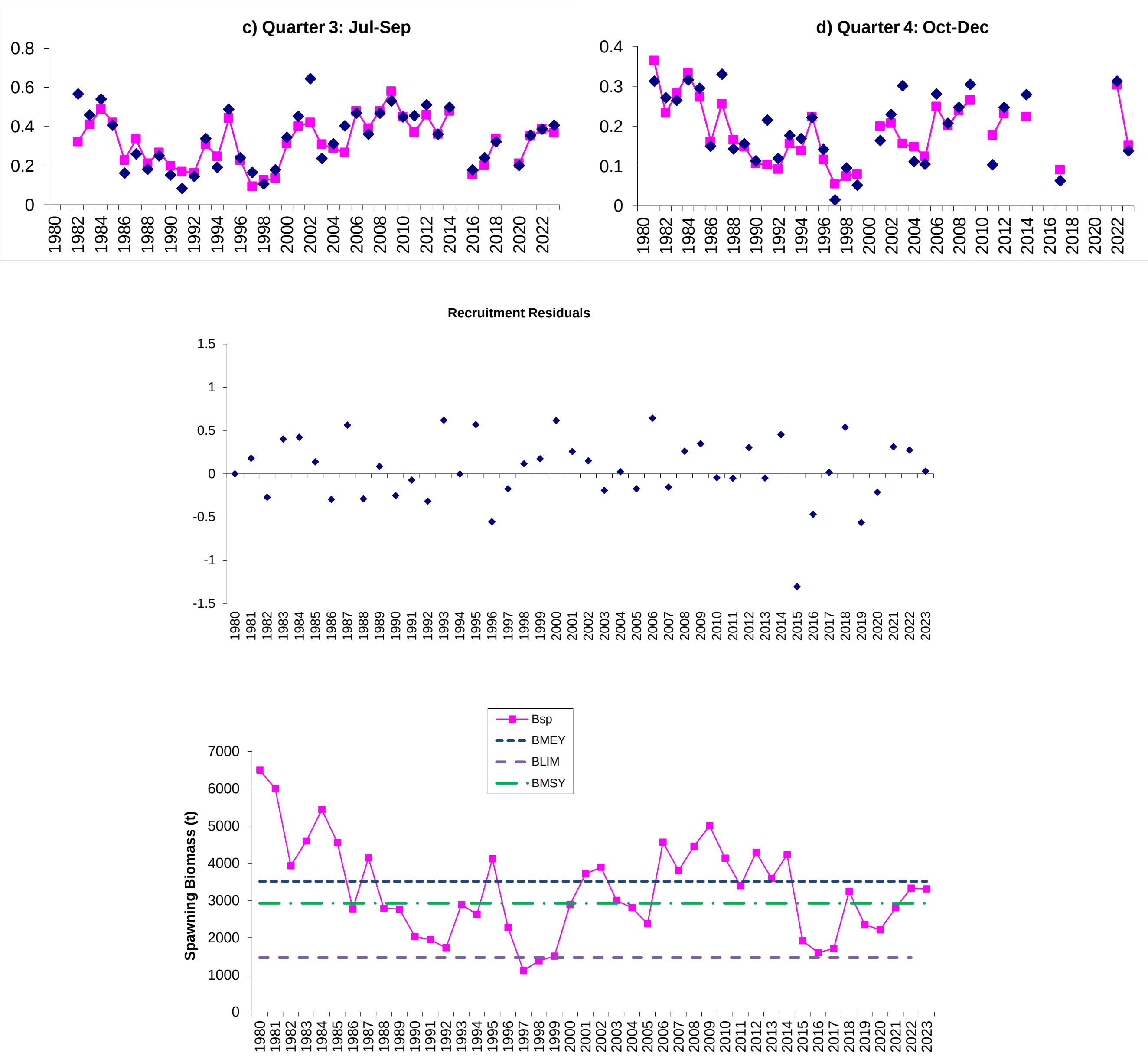
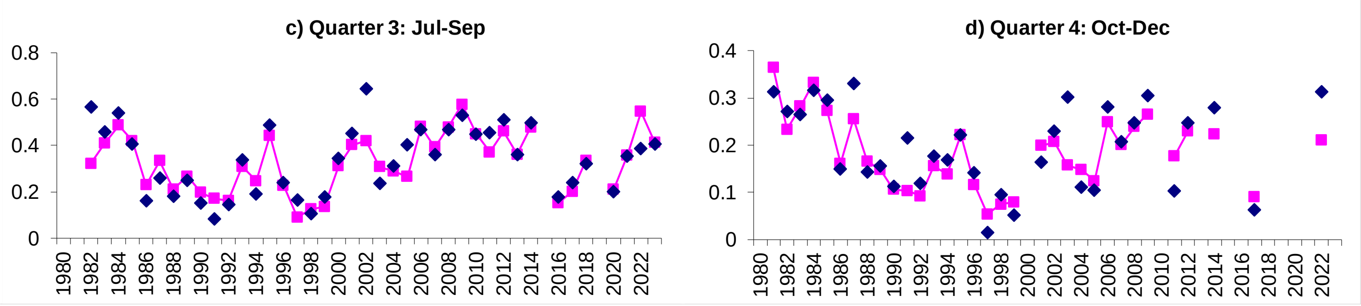
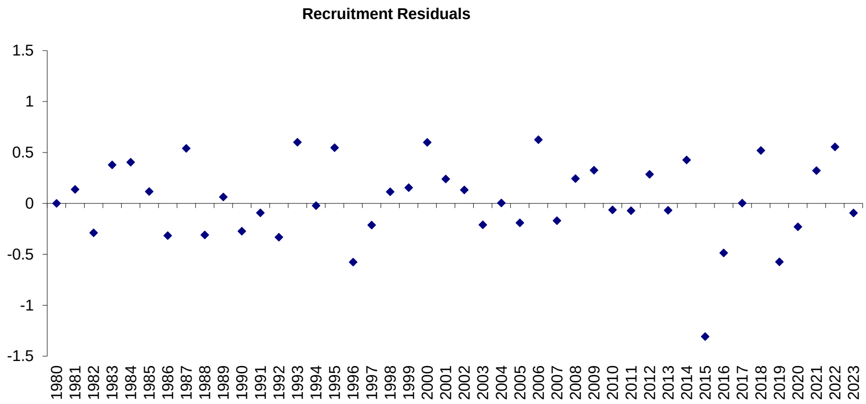


Figure 13. Selected results from sensitivity test (D), which excluded the 4th quarter CPUE estimate for 2023 due to its being based on only 20 boat days.





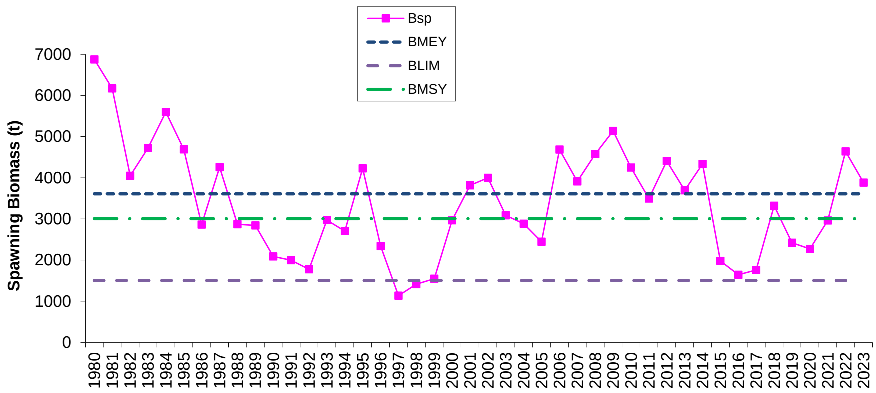
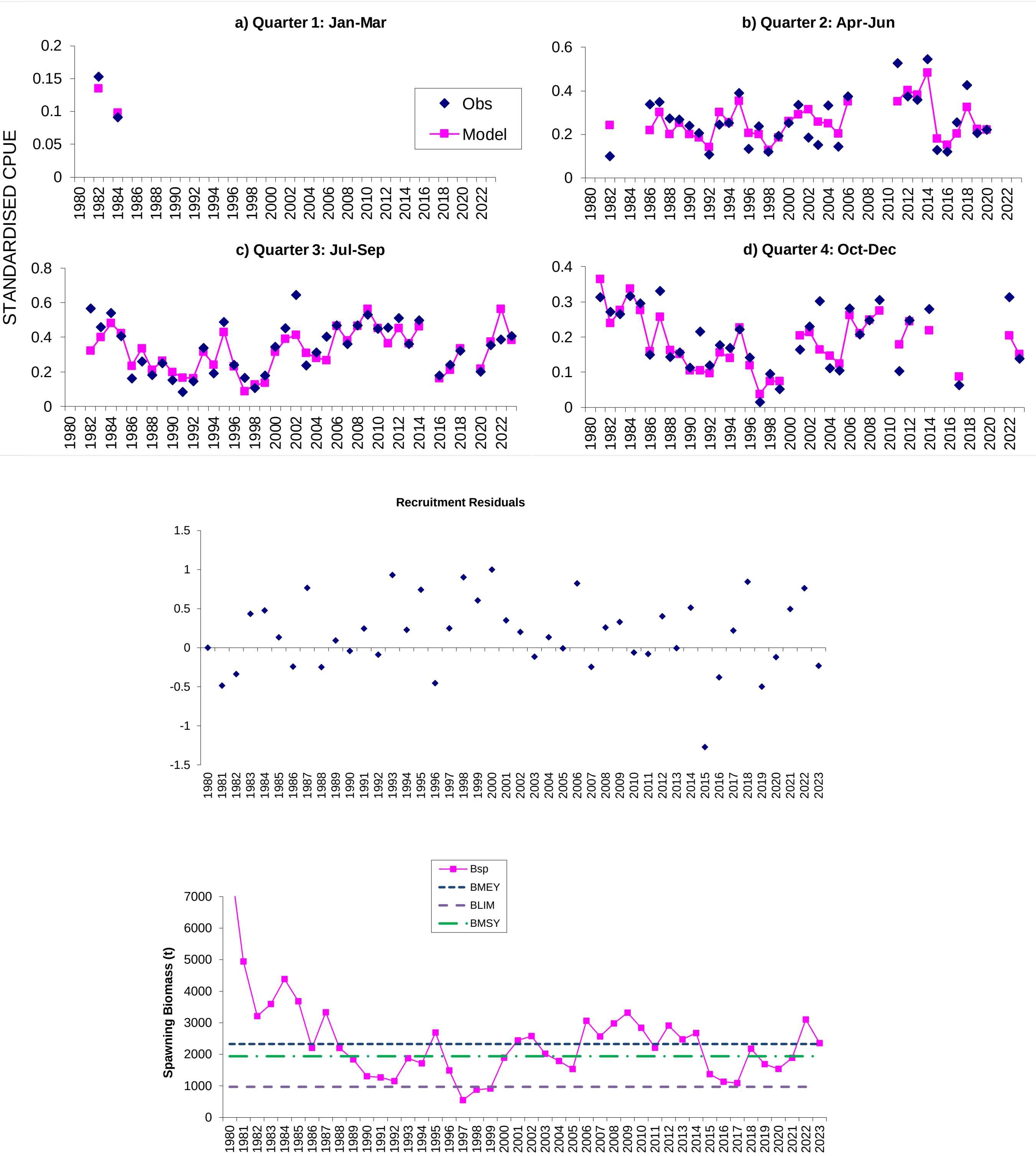


Figure 14. Selected results from sensitivity test (E) involving estimating the natural mortality parameter *M*.



5.4 Environmental drivers and revisions to the Harvest Strategy

Previous work (Plagányi et al. 2016, 2020) hypothesized that low Redleg catches in 2015-2016 could be explained by temporary drops in sea level and rainfall potentially reducing the ability of postlarvae to reach their nursery ground. It was proposed that notably poor prawn catch years may be predicted using two variables that are a sub-set of possible drivers of recruitment - the January Southern Oscillation Index and the combined January to February cumulative rainfall. However, due to challenges in verifying and defining such environmental relationships for inclusion in a stock assessment, development of a harvest strategy framework was proposed to support management recommendations.

A Harvest Strategy framework was thus developed using two pragmatic empirical measures, SOI (January) and rainfall (cumulative January to February), as indicators of a poor versus good prawn season. Uncertainty in the exact mechanism of these environmental drivers on the stock can be accounted for using a MSE framework, and uncertainty pertaining to prediction of future low catches in poor environmental (El Niño) can be accounted for as part of MSE testing (Blamey et al. 2020). The MSE testing can then evaluate the efficacy of alternative harvest strategies to reduce the risk of the stock decreasing below limit or target levels, as well as the risk of sub-economic fishing.

The MSE framework was used to simulation test whether the Harvest Strategy is sufficiently robust (e.g. reduces risk of stock decreasing below BLIM) to changes in fishing effort or fishing pattern, including anomalous scenarios for which there have previously not been data available to assess this. Based on the results presented in Blamey et al. (2020, 2021) and subsequent discussions with stakeholders, the first season was permanently closed to Redleg Banana Prawn fishing with effect from 2021.

As we collect more data over the next few years, our understanding of environmental drivers (Plagányi et al. 2021) and other effects such as economic factors (Pascoe et al. 2020), which are currently confounded, will improve and in turn will allow us to improve the models and management of this fishery, especially under a changing climate (see also Appendix 4). However, in the absence of a fishery-independent survey it will be very difficult to attribute the effects of multiple factors on the fishery.

6 Benefits and Adoption

The assessment provided estimates of stock status for the Redleg Banana Prawns. The outcome provided will be a demonstration of the sustainability of the NPF target species under current management. In accordance with the NPF Harvest Strategy the predictive component of the models supported recommendations for the Total Allowable Effort (TAE) for Redleg Banana Prawns (2024) (where previous years were published before), thus 2024 is presented in this report.

As the primary clients of this work are the management group of the fishery, that is AFMA, NORMAC, NPRAG and NPF Industry – principal methods were communicated via the provision of progress reports to meetings of these groups, and the use of the various forums to provide feedback on the project outputs. Presentations of all the work in this project were provided at all the NPRAG meetings during the time frame of this project. There is a public record of the minutes of the meetings, and the recommendations for the TAE for each year that were endorsed by the NPRAG and NORMAC, which would have been sent on to the AFMA Commission.

7 Further Development & Planned Outcomes

This project is in its final phase of the three-year NPF Assessment project commenced in July 2021 (2021-2024). This project has been achieving the same set of objectives as outlined and delivered previously, although under new and different circumstances and challenges. Given the critical importance of this fishery to the nation as a key Commonwealth fishery its ongoing assessment in terms of biological sustainability needs to be maintained.

8 Conclusion and Recommendations

The stock assessment was reviewed and adopted by the NPRAG at the June 2024 meeting. The Reference Case model estimated that the stock is currently at 117% of the BMSY level and approximately at the target BMEY level (Table 5; see also Appendix 1). The Reference Case recommended TAE for 2024, with no fishing in first season, is 412 boat days (90% confidence interval [300;524]), with a corresponding catch prediction of 683 [351;768] tonnes. Thus, a predicted 94% increase in effort from the previous year (and a 169% increase in catch noting the comments as above). The positive forecast for 2024 is because the model estimates that the stock has fully recovered to the target level in 2023 (i.e. Bsp_{2023}/B_{MEY} = 98%).

Table 5 Summary of recommended TAE and predicted catch for 2024.

Recommended TAE 2024	412 boat days
Predicted Catch 2024	683 tonnes

Table 6 Summary of Redleg Banana Prawn stock status relative to Reference levels

Parameter	Redleg Banana Prawn (JBG)
Steepness	0.6
Catch (2023) (tonnes)	254
BMEY/BMSY	1.20
B_{2021}/BMSY	0.98
B_{2021}/BMEY	0.82
B_{2022}/BMSY	1.53
B_{2022}/BMEY	1.28
B_{2023}/BMSY	1.17
B_{2023}/BMEY	0.98

When evaluated retrospectively, spawning biomasses since 2021 have been at or above BMSY and fluctuating about BMEY. In recent years the actual fishing mortality was less than the target fishing mortality rate. The 2023 observed effort of 212 boat days was below the effort level that would have been recommended given actual recruitment.

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10 Appendices

Appendix 1. The Production Model

A discrete population model was constructed for Redleg Banana Prawns in the JBG as follows. The model time-step is quarterly (3 month quarters), with the number of prawns in year *y* and quarter *s* ($N_{y,s}$) given by:

$$N_{y,s+1} = N_{y,s}\, e^{-M_s} - C_{y,s} + R_{y,s+1} \qquad \text{for } s = 1 \text{ to } 3 \qquad (1)$$

and

$$N_{y+1,1} = N_{y,4}\, e^{-M_4} - C_{y,4} + R_{y+1,1} \qquad \text{for } s = 4 \qquad (2)$$

where

$N_{y,s}$ is the number of recruited and mature prawns (those corresponding to a size large enough to be fished) at the start of quarter s in year y (which refers to a calendar year),

$R_{y,s}$ is the number of recruits (number of 6-month old prawns) which are added to the population at the end of each quarter s in year y,

M_s denotes the natural mortality rate during quarter s (assumed in the Reference case to be constant throughout the year), and computed by multiplying the weekly natural mortality rate estimate by 13 (weeks) to reflect a quarterly mortality rate; and

$C_{y,s}$ is the predicted number of prawns caught during quarter s in year y, with catches arbitrarily assumed taken as a pulse at the end of each quarter.

Given catches are recorded in units of mass, the predicted number of prawns caught during quarter s in year y is computed from the following relationship:

$$C_{y,s} = A_{y,s} F_{y,s} N_{y,s} e^{-M_s} \qquad (3)$$

where

$A_{y,s}$ is the relative availability for quarter s and for year y, with one availability vector being applied to the early period 1970-1987, another vector to the period 1988-2006 (i.e. post end of year NPF closure) and 2007-2010 (first season closure) periods; and

$F_{y,s}$ is the fished proportion in quarter s and year y of a fully selected age class.

The fished proportion reflects the catch by mass ($C^{mass}{}_{y,s}$) in quarter s and year y as a proportion of the exploitable ("available") component of biomass:

$$F_{y,s} = C^{mass}{}_{y,s} \big/ B^{ex}_{y,s} \qquad (4)$$

with

$$B^{ex}_{y,s} = w_s N_{y,s} e^{-M_s} A_{y,s} \qquad (5)$$

where

w_s is the average mass of prawns during quarter s.

One of the biggest challenges in constructing a realistic model of P. indicus relates to improved information on growth, and in particular quarterly changes in growth. Length frequency data that span a number of periods through the year are needed to better inform this aspect of the model. This model used the female (because the male growth is too slow on its own) von Bertalanffy growth parameters and assumed that individual mass increases through the year. An average length and mass of prawns was thus calculated for each quarter, assuming a median birth date of October.

The number of recruits at the end of quarter s in year y is assumed to be related to the spawning stock size six months previously (i.e. during two quarters previously) by a modified Beverton-Holt stock-recruitment relationship (Beverton and Holt, 1957), allowing for annual fluctuation about the deterministic relationship for Quarters 1 and 2:

$$R_{y,s+1} = \frac{\alpha B^{sp}_{y,s-1}}{\beta + \left(B^{sp}_{y,s-1}\right)^{\gamma}} e^{(\varsigma_{y,s} - (\sigma_R)^2/2)} \qquad s = 1, 2$$

$$R_{y,s+1} = \frac{\alpha B^{sp}_{y,s-1}}{\beta + \left(B^{sp}_{y,s-1}\right)^{\gamma}} \qquad s = 3,4 \tag{6}$$

where

α, β and γ are spawning biomass-recruitment relationship parameters (note that cases with γ > 1 lead to recruitment which reaches a maximum at a certain spawning biomass, and thereafter declines towards zero, and thus have the capability of mimicking a Ricker-type relationship – the Reference Case has $\gamma = 1$),

$\varsigma_{y,s}$ reflects fluctuation about the expected recruitment for year y and quarter s, which is assumed to be normally distributed with standard deviation □R (which is input in the applications considered here); these residuals are treated as estimable parameters in the model fitting process, and a single set of residuals is estimated for Quarters 1 and 2 because almost all recruitment is assumed to occur during this half of the year and is assumed driven by the same environmental influences each year;

$B^{sp}_{y,s}$ is the spawning biomass at the start of quarter s in year y, computed as:

$$B^{sp}_{y,s} = f_s \cdot w_s \cdot N_{y,s} \tag{7}$$

where

f_s is a relative index of the amount of spawning during quarter s.

In order to work with estimable parameters that are more meaningful biologically, the stock-recruitment relationship is re-parameterised in terms of the pre-exploitation equilibrium spawning biomass, B^{sp}_o, and the “steepness”, h, of the stock-recruitment relationship, which is the proportion of the virgin recruitment that is realized at a spawning biomass level of 20% of the virgin spawning biomass. Equation (6) can be rewritten in terms of the “steepness” h, defined as the fraction of pristine recruitment R_0 that results when spawning biomass drops to 20% of its pristine level, i.e.:

$$hR_0 = R\left(0.2B^{sp}_0\right) \tag{8}$$

which yields the following for the deterministic component of the formulation:

$$R\left(B_{y,s}^{sp}\right)=\frac{4h\cdot R_0\cdot B_{y,s}^{sp}}{B_o^{sp}\left(1-h\right)+B_{y,s}^{sp}\left(5h-1\right)} \tag{9}$$

It follows that the total spawner stock size and recruitment for calendar year y are given respectively by:

$$B_y^{sp}=\sum_s B_{y,s}^{sp} \tag{10}$$

$$R_y=\sum_s R_{y,s} \tag{11}$$

The resource is assumed to be at the deterministic equilibrium (corresponding to an absence of harvesting) at the start of 1980, the initial year considered here. The model estimates the pre-exploitation quarter 1 spawning biomass, from which the starting number of prawns can be calculated using Equation (7), and it follows:

$$R_{0,1}=\left(1-e^{-M_1}\right)\cdot B_{0,1}^{sp}/\left(f_1\cdot w_1\right) \tag{12}$$

and similarly for the pristine numbers and recruitment levels in the remaining quarters, which can then be added together to provide total spawning biomass and recruitment values for the year. The model sets the starting spawning biomass in the first quarter $B_{0,1}^{sp}=K^{sp}$. Given the total pre-exploitation spawning biomass B_0^{sp}, it follows that:

$$B_0^{sp}=\frac{\sum_s f_s\cdot w_s\cdot R_{0,s}}{\left(1-e^{-M_s}\right)} \tag{13}$$

which can be solved for *R₀*, and hence the stock recruit parameters.

Likelihood function

The model is fitted to all available CPUE data for each of the four quarters. The likelihood contribution is calculated assuming that the observed abundance index is log-normally distributed about its expected value:

$$I_y^s = \hat{I}_y^s e^{\varepsilon_y^s} \qquad \text{or} \qquad \varepsilon_y^s = \ln(I_y^s) - \ln(\hat{I}_y^s) \tag{14}$$

where I_y^s is the abundance index (with fishing power effect added) for year *y* and quarter *s*,

$\hat{I}_y^s = q^s B_{y,s}^{ex}$ is the corresponding model estimated value, where $B_{y,s}^{ex}$ is the model value for exploitable resource biomass corresponding to quarter *s*, given by equation (5).

q is the constant of proportionality which is assumed to be the same for each of the quarters, and

ε_y^s from $N\left(0, \left(\sigma_y^s\right)^2\right)$.

In cases where a hyperstability relationship is assumed, the hyperstability is implemented by modifying the relationship as follows $\hat{I}_y^s = q^s \left(B_{y,s}^{ex}\right)^{hyp}$, where *hyp* is the hyperstability parameter (which is set to unity in scenarios with no hyperstability).

The contribution to the negative of the log-likelihood function (after removal of constants) is given then by:

$$-\ln L = \sum_y \left[\sum_s \ln \sigma_y^s + \left(\varepsilon_y^s\right)^2 / 2\left(\sigma_y^s\right)^2 \right] \tag{15}$$

with the standard deviation of the residuals for the logarithms of the abundance series assumed to be independent of *y*, and set in the fitting procedure by its maximum likelihood value:

$$\hat{\sigma}^s = \sqrt{\frac{1}{n}\sum_y \sum_s \left(\ln I_y^s - \ln \hat{I}_y^s\right)^2} \qquad (16)$$

where n is the number of data points across all years and quarters.

The catchability coefficient q is also estimated using maximum likelihood:

$$\ln \hat{q} = \frac{1}{n}\sum_y \sum_s \left(\ln I_{y,s}^s - \ln \hat{B}_{y,s}^{ex}\right) \qquad (17)$$

Stock-recruitment function residuals

The stock-recruitment residuals are assumed to be log-normally distributed. Thus, the contribution of the recruitment residuals to the negative of the (now penalised) log-likelihood function is given by:

$$-\ell n L^{pen} = \sum_{y=y1+1}^{y2} \left(R_{y,s}\right)^2 \Big/ 2\sigma_R^2 \qquad (18)$$

where

σ_R is the standard deviation of the log-residuals, which is input.

Reference Levels

There are few data to inform calculation of MEY for Redleg Banana Prawns. Instead, NPF stakeholders have in the past agreed that a suitable proxy of B_{MEY} that could be used would be to calculate the average level of the stock over a historical reference period (1999-2010) when the fishery was considered to be operating in an optimal manner on average. The B_{MEY} reference level is therefore computed annually as the average spawning biomass level over the historical reference period. In lieu of precise estimation of MEY, the default assumption is that it is achieved at a biomass level corresponding to 1.2 times the biomass required to achieve MSY (Smith et al. 2013). This default is thus in turn applied to the B_{MEY} level (a proxy that is calculated based on historical reference period) to derive the B_{MSY} reference level as well as the B_{LIM} which is similarly computed based on the default that B_{LIM} =0.5 B_{MSY}.

As part of the Redleg Stock assessment Revision Project (Plagányi et al. 2022), and in consultation with stakeholders, the appropriateness of these reference levels was reviewed. Available industry representatives felt that the current proxy B_{MEY} remains a reasonable target level but that this could be reviewed in a few years if necessary as further insights are provided by changes in the operation of the fishery going forward as well as future changes to price and costs. It may also be possible to refine these estimates in future based on more detailed economic calculations that account also for the multispecies nature of the fishery.

The exact value for the B_{MEY} and other reference levels thus depends on the stock assessment and needs to be re-estimated with each stock assessment update. The 2022 reference levels for B_{MEY}, B_{MSY}, and B_{LIM} are respectively 3534t, 2945t and 1473t.

As previously, for years when the spawning biomass decreases below a pre-specified reference level, a hockey-stick rule is applied to adjust the fishing effort downwards but this rule was modified (Figure 12) to start the decreasing limb at BMSY rather than BMEY given that due to natural variability in the stock, fluctuations around BMEY are to be expected. Second, rather than specifying that *F* should be set to zero when the spawning biomass is estimated to be below the LRP in any single year, the rule takes into account that the LRP needs to be breached for two years before the fishery is closed. This is also to account for the highly-variable nature of the stock and hence circumvents unnecessarily closing the fishery in a year when it may not be necessary.

In addition, it wasn't considered pragmatic to do a linear extrapolation down to zero to compute F when B_{sp} is less than LRP (Figure 12). This is first because there is considerable uncertainty associated with the stock assessment given that it relies solely on CPUE and fishing power data. There has also historically been reasonably substantial differences between the TAE and the actual observed fishing effort in any year, such that there is in any case insufficient precision to support use of a very precise estimate, particularly given that the corresponding number of boat days available to inform estimates of CPUE may be low and hence compromise the reliability of associated CPUE estimates.

Future projections

Resource biomass was projected forward under both input - and output control scenarios. A TAC was computed for each year based on a target total fishing mortality rate. However forward projections are complicated because of inter-annual changes in the fishing effort and hence mortality rate applied per season/quarter. The Reference Case model typically assumes that the future pattern of fishing effort per quarter will be similar to recent observed fishing effort distribution (e.g. the average of the last 3-years or 5-years) but this is reviewed annually in consultation with stakeholders as over time there have been changes to fishing operations and the opening of the first season. The target fishing mortality (see next section) per quarter s (F_s^{targ}) therefore depends on how the fishing effort is distributed each year.

The future projected number of prawns caught during quarter s in year y is therefore computed from the following relationship:

$$\hat{C}_{y,s} = F_s^{targ} \hat{B}_{y,s}^{ex} \qquad (19)$$

Based on the above and Equation (14), an estimate of the predicted fishing effort (days) is thus calculated as follows:

$$\hat{E}_{y,s} = \frac{\hat{C}_{y,s}}{\theta_{y*} q \hat{B}_{y,s}^{ex}} \qquad (20)$$

Where θ_{y*} is the fishing power for year y*, which represents the last year in the series (i.e. fishing power is held constant at the most recent level for future projections).

Table A.1 Reference Case model recruitment residual parameter estimates and associated 90% confidence interval calculated using Hessian-based standard deviations

	Value	90% confidence interval	
1981	0.17	-0.52	0.86
1982	-0.27	-0.85	0.30
1983	0.40	-0.02	0.82
1984	0.42	-0.09	0.94
1985	0.13	-0.38	0.65
1986	-0.30	-0.79	0.19
1987	0.56	0.16	0.96
1988	-0.29	-0.75	0.16
1989	0.08	-0.44	0.60
1990	-0.26	-0.67	0.16
1991	-0.08	-0.48	0.33
1992	-0.32	-0.74	0.10
1993	0.61	0.26	0.97
1994	-0.01	-0.41	0.40
1995	0.56	0.18	0.95
1996	-0.56	-1.03	-0.09
1997	-0.18	-0.62	0.26
1998	0.12	-0.25	0.48
1999	0.17	-0.19	0.52
2000	0.61	0.19	1.03
2001	0.25	-0.18	0.69
2002	0.15	-0.27	0.57
2003	-0.19	-0.63	0.24
2004	0.02	-0.39	0.43
2005	-0.18	-0.60	0.25

2006	0.64	0.24	1.03
2007	-0.15	-0.66	0.35
2008	0.26	-0.22	0.74
2009	0.34	-0.13	0.82
2010	-0.05	-0.67	0.57
2011	-0.06	-0.57	0.46
2012	0.30	-0.12	0.72
2013	-0.05	-0.54	0.43
2014	0.45	0.04	0.86
2015	-1.30	-2.08	-0.52
2016	-0.47	-1.01	0.07
2017	0.01	-0.40	0.43
2018	0.53	0.09	0.98
2019	-0.56	-1.25	0.12
2020	-0.22	-0.76	0.33
2021	0.31	-0.25	0.87
2022	0.24	-0.30	0.78

Appendix 2. Biological Information

- Tag-recapture data are available from field tagging and release experiments in the JBG by Die et al. (2002). These data suggest fairly high natural mortality of ca. 0.05 wk^{-1}. The maximum age of Redleg Banana Prawns is thought to be 12-15 months given no tagged prawns were caught in the year after tagging.
- There are large differences between the growth rates for male and female *P. indicus*, with the latter growing much faster. Parameter estimates for males (κ = 0.0103; L_∞ = 34.05 mm and t_0 = -0.06) and females (κ = 0.0053; L_∞ = 49.64 mm and t_0 = -0.34) were obtained from Loneragan et al. (2002) who used the Wang (1995) growth model. Length-weight relationships are taken from Loneragan et al. (1997):
  - Females Weight (g) = 0.000889 CL (mm) $^{2.914}$
  - Males Weight (g) = 0.000372 CL (mm) $^{3.197}$
- The average weights (grams) of *P. indicus* landed in the JBG by Newfishing Australia range from 25.6 to 40.7 g (Loneragan et al. 2002). The average weights per prawn recorded for six commercial categories ranged from 11g to 57g. Raw length frequency data would be highly informative in developing a model.
- Loneragan et al. (2002) found no significant differences in the growth of the exploitable phase of *P. indicus* between two years characterised by very different recruitment levels, suggesting there are not overly strong density-dependent effects on growth for this species. The population dynamics are likely driven by variability in recruitment levels given the considerable distances between the recruitment and spawning grounds (Kenyon et al. 2004, Manson et al. 2001).

Spawning and maturity

- The size of females at first maturity is 25 mm CL (and 23 mm for males) with the size at mass spawning (defined as corresponding to 50% of females having visible ovaries) is 44 mm CL (Taylor 2002). Female *P. indicus* carry fewer eggs than White Banana Prawns, and substantially less than Tiger Prawns.
- Loneragan et al. (1997) analysed data on the stage of maturity for female *P. indicus* and concluded that the proportion of mature females is low during April to September and high over the period October to March. Using length frequency data from NT Fisheries, their rough analysis suggested that a peak in recruitment occurs in March,

with 95% of recruits arriving between December and April. Based on the above, the model assumes peak spawning over October to March with substantially lower levels of spawning during the rest of the year.

The Reference Case model assumes that the proportion of the recruited population (i.e. individuals large enough to be recruited to the fishery) that spawn at the start of each of quarters 1-4 are as shown in Table 3. These proportions represent a combination of factors, including that not all prawns may be large enough to spawn and that not all mature prawns may spawn at that time. Assuming (based on the growth curve information) a roughly 6-month growth period before individuals are large enough to recruit to the fishery. this means that peaks in recruitment to the model population will occur at the ends of March and June. As this constitutes the bulk of the recruitment, recruitment residuals are estimated for the April to June quarter only.

Appendix 3. Data Inputs

For May 2023 Reference Case assessment, we applied the following rules:

1. Require total annual Effort (boat days) >= 70 for a stock assessment to be conducted
2. Minimum quarterly total boat days = 20 for each of quarters 2 and 3 data, for the corresponding CPUE to be included in the assessment (this rule is applied retrospectively also in case a stock assessment is not run in any year not meeting criterion (1) above).
3. Minimum quarterly total boat days = 20 for quarter 1 historical data
4. Minimum quarterly total boat days = 20 for quarter 4 CPUE data to be included in the assessment

   Application of the data rules in the current assessment resulted in excluding the following CPUE data from the model fitting process: 2013 quarter 4; 2015 quarter 3; 2018 quarter 4; 2019 quarters 3 and 4; 2020, 2021 quarter 4 (Table A3.1).

Table A3.1. Summary of the number of boat days per quarter, highlighting cases with n<20. na represents confidential data due to less than 5-boat day rule.

	Q1	Q2	Q3	Q4
2007	0	0	117	98
2008	0	0	139	22
2009	0	0	289	103
2010	0	0	197	17
2011	0	84	229	148
2012	0	22	107	20
2013	0	233	124	na
2014	0	216	299	44
2015	0	73	6	0
2016	0	52	24	0
2017	0	80	363	105
2018	0	103	105	5
2019	0	72	na	na
2020	0	147	39	9
2021	0	0	398	16
2022	0	0	396	115

Appendix 4. Environmental Indicators for the Redleg Banana Prawn sub-fishery

The Australian Fisheries Management Authority (AFMA) have mandated that climate change information be incorporated into Commonwealth fisheries decision making processes. Hence, there is now a standing agenda item on climate change at all RAG and MAC meetings where TACs or TAEs are being considered and climate and ecosystem status report cards are being developed for commonwealth fisheries, including the Redleg Banana Prawn sub-fishery (CSIRO 2023 - Attachment A – Climate and ecosystem status report 2023 for the JBG, NPRAG 24-25 May 2023 Agenda Item 4b).

The best available scientific information suggests that the abundance (and catchability) of Redleg Banana Prawns is influenced by a combination of summer rainfall and El Niño or La Niña events (Plagányi et al. 2021). The harvest strategy has thus been MSE tested to ensure that it is resilient to the extreme variability in stock abundance that may occur during El Niño and La Niña events (Blamey et al. 2022), defined respectively as when the Southern Oscillation Index (SOI) falls below a value of -7 or above +7. Recent research (Cai et al. 2023) confirms that human-caused greenhouse emissions are resulting in more intense and more frequent El Niño and La Niña events, as well as more frequent swings from a strong El Niño to a strong La Niña event the following year. The Redleg Banana Prawn harvest strategy has thus been adapted to improve its robustness to extreme climate variability (Blamey et al. 2022, Plagányi et al. 2023).

Table A4.1. Monthly Southern Oscillation Index (SOI) for 2016-2023 with La Niña and El Niño events highlighted in green and red respectively.

Southern Oscillation Index monthly data

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2023	**11.8**	10.5	-2	0.3	-	-	-	-	-	-	-	-
2022	**4.1**	8.2	13.8	22.6	17.1	21.2	8.7	9.1	18.3	17.7	4.6	20
2021	**16.5**	11.5	−0.3	2	3.6	2.6	15.9	4.6	9.3	6.7	12.5	13.8
2020	**1.3**	−2.2	−5.2	−0.5	2.8	−9.6	4.2	9.8	10.5	4.2	9.2	16.9
2019	**−0.6**	−13.5	−6.8	−1.3	−9.0	−10.4	−5.6	−4.4	−12.4	−5.6	−9.3	−5.5
2018	**8.9**	−6.0	10.5	4.5	2.1	−5.5	1.6	−6.9	−10.0	3	−0.1	9.3
2017	**1.3**	−2.2	5.1	−6.3	0.5	−10.4	8.1	3.3	6.9	9.1	11.8	−1.4
2016	**−19.7**	−19.7	−4.7	−22.0	2.8	5.8	4.2	5.3	13.5	−4.3	−0.7	2.6

SOI (Jan 2023) = +11.8 (La Nina)
2023 Update: Jan&Feb rainfall = 694 mm > median
Expect very good CPUE for 2023

- if SOI<-7 and rainfall <median: poor CPUE
- if SOI<-7 and rainfall>median: average to high CPUE
- **if SOI>+7 and rainfall>median: very good CPUE**
- if SOI>+7 and rainfall<median: low-average CPUE
- neutral zone – (less certain) low to average CPUE

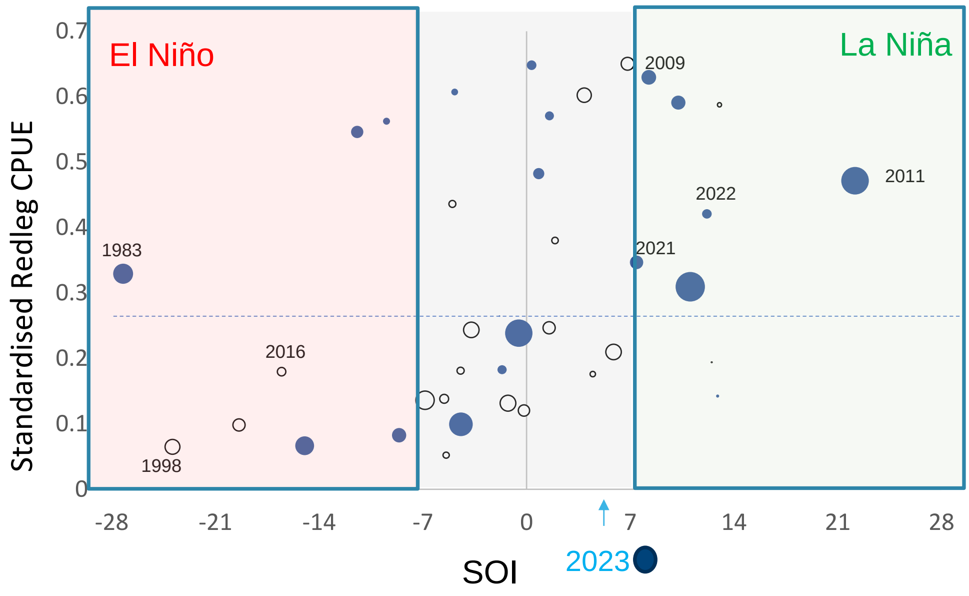
	Argyle	Kingston Newry MtSanford
Median (1983-2015)	358	391.35 361.3 322.7

Note that the persistence of La Niña conditions throughout 2022 was unusual and the only year with some similarity was 1989 hence there is uncertainty as to what the implications might be. It was noted last year that it is even more unusual that meteorologists forecasted that a rare ‘triple’ La Niña climate event over the summer (wet season) was considered likely with La Niña conditions persisting into the 2022/2023 summer (Jones 2022). This has happened only twice since 1950 and could be natural variability, but climate change may also make these conditions more likely in future (Jones 2022). As clear from Table A4.1, the La Niña conditions persisted into February 2023.

In the analyses of Plagányi et al. (2021) the SOI and rainfall indicators were chosen using only information available before March each year (e.g., January SOI and combined January-February rainfall), in order to align with the first season fishery opening. However, given the first season is now closed to fishing, the analysis has been preliminarily revised using instead all available data to inform the key environmental indicators (i.e., rainfall and SOI from January to April) (Figure A4.1). This is also because the SOI index has been quite variable during the first few months of the year – for example, the January 2022 index did not indicate a La Niña year as should have been the case based on the February to October indices. Moreover, the 2023 Jan-Feb SOI switches to neutral values during

March -April, so that the average SOI is slightly below the La Niña cut-off, whereas rainfall is above average, so there is some confidence that CPUE will be above average using this revised model, noting that it is still under investigation. The current BOM forecast for winter 2023, and presumably into summer 2023/2024, is for an El Niño watch, meaning 2024 may not be as favourable for Redleg Banana Prawns.

Figure. A4.1. Relationship between JBG *P. indicus* August standardised CPUE (tonnes/day) (vertical axis) and January-April average SOI (horizontal axis), with the area of the bubbles representing size of positive (blue fill) or negative (empty circles) differences between the January to April cumulative rainfall index and the median over 1983-2016, i.e., larger area of circle indicates farther from the mean. The horizontal dashed line shows median CPUE, and the grey shaded area separates the El Niño (SOI<-7) and La Niña (SOI>7) years from the neutral zone for which the model has less predictive ability. The model shows mostly very poor CPUE during El Niño episodes versus very good CPUE during La Niña episodes with the deviations from this pattern largely explained by whether the cumulative January to April rainfall is above or below the median.



SOI is the average of Jan-Apr; CPUE is average over weeks 32-35; Rainfall is total Jan-Apr relative to median (1983-2022)

SOI = Southern Oscillation Index

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