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Revision of the Assessment Model for the Redleg Banana Prawn (*Penaeus indicus*) in the Joseph Bonaparte Gulf Fishery

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AFMA Project No. 2019/0843: Revision of assessment model for Redleg banana prawns

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

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Acronyms

AFMA	Australian Fisheries Management Authority
B_{LIM}	Biomass Limit reference level
B_{MEY}	Biomass level of Maximum Economic Yield
B_{MSY}	Biomass level of Maximum Sustainable Yield
CPUE	Catch Per Unit Effort
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CV	Coefficient of Variation
FRDC	Fisheries Research and Development Corporation
FTARG	Target Fishing mortality rate
GoC	Gulf of Carpentaria
HCR	Harvest Control Rule
HS	Harvest Strategy
JBG	Joseph Bonaparte Gulf
LRP	Limit Reference Point
MEY	Maximum Economic Yield
MSE	Management Strategy Evaluation
MSY	Maximum Sustainable Yield
NPF	Northern Prawn Fishery
NPFI	NPF Industry Pty Ltd
NPRAG	Northern Prawn Fisheries Resource Assessment Group

NORMAC	Northern Prawn Fishery Management Advisory Committee
NTDPI	Northern Territory Department of Primary Industries
OM	Operating Model
RAG	Resource Assessment Group
TAE	Total allowable effort

Executive Summary

The need for revisions to the Redleg Banana Prawn *Penaeus indicus* stock assessment model for the Joseph Bonaparte Gulf (JBG) has been discussed at a number of previous NPRAG meetings since 2019 as well as at the annual NPF research workshop in 2020 and 2021. This led to recognition of the need to revise the Redleg Banana Prawn stock assessment model to account for changes in the Harvest Strategy (HS), fishing behaviour, environmental drivers that have impacted the fishery, low data availability in some years, as well as large uncertainties in stock size given there is no fishery-independent survey for this fishery. This study revised and implemented a number of changes to the Redleg Banana Prawn stock assessment based on the outcomes of the Redleg MSE project and to better align with the changes to the HS. Further changes to the Redleg Banana Prawn assessment model will be incorporated in the 2022 stock assessment model, with a focus on meeting the requirement for the current HS, including refinement of outputs for recommended TAE. The revised HS will use a substantially lower data (effort) cut-off to underpin the definition of data-sufficient versus data-insufficient years for deciding whether or not a stock assessment will be run in any year. Hence for all data-sufficient years, the stock assessment will be used to estimate the stock depletion level relative to the target and limit reference points. Where effort is very low the associated total catch is also expected to be low, and is considered not to add greatly to fishing mortality (except in the case where the limit reference point has been breached once, as per revised HS). It was recommended that the CPUE empirical rule previously incorporated in the HS is no longer necessary. Following review of the reference point values used for Redleg Banana Prawns, the current proxy B_{MEY} remains a reasonable target level but that this could be re-reviewed in a few years if necessary. Minor revisions have been made to the so-called ‘Hockey-Stick Rule’ used in the HS, in particular to cover the (unlikely) situation should the stock be estimated to decrease below the Limit Reference Point (LRP) in a single year. Preliminary analyses suggest a monthly average CPUE of 500 kg/day would be a useful voluntary trigger to guide fishers to limit effort whenever there are indications that the stock biomass is reduced or CPUE is less favourable. Analysis of size grade data showed that the larger prawns are usually caught in the second season supporting one of the rationales behind the recently adopted change to the HCR. Analyses also suggest that the quantity of U10 prawns caught in August could be

a possible indicator for whether the fishing season (season 2) is likely to be a good or poor season. We recommend that the two key environmental indicators - the January Southern Oscillation Index and the combined January to February cumulative rainfall - continue to be collected and assessed on an annual basis. We also recommend ongoing collection and analysis of available price data for Redleg Banana prawns to assist in improving understanding of economic drivers. Under low data conditions, the main concern from a fishing power perspective is related to bias and hence the data-sufficient number also needed to be large enough so that the fishing power can be estimated for that year (e.g. the model is able to converge). Retrospective model simulations were run to inform final choice of a minimum number *nmin* of boat days that can be used to define a data-sufficient year. From a stock assessment perspective, we assumed a reasonable acceptable error in assessment of the stock status is 10%, noting that more than this would risk (in particular over-estimating) the B_{LIM} rule being incorrectly triggered or incorrectly not triggered. The 10% cut-off is consistent with the Commonwealth Harvest Strategy Policy to “maintain all commercial fish stocks, including byproduct, above a biomass limit where the risk to the stock is regarded as unacceptable (B_{LIM}), at least 90 per cent of the time”. These analyses suggested that the final choice of *nmin* is likely to be in the range 60-80 boat days days and at the upper end of the range. Further support for choice of *nmin* is because there is a historical precedent for 72 days in 2019, when the fishing power model converged and the stock assessment model was applied. The February 2022 NPRAG agreed that the suitable minimum threshold to run a Redleg Banana Prawn assessment be set at 70 total fishing days. This threshold should be reviewed in 3 years (2025) to enable the consideration of the impacts of the first-season closure on the data availability and assessment (when updated data will be available). If there are substantial changes in the fishing pattern and they are unprecedented this would also point to the need to consider review, as our study focused on past fishing patterns.

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Acknowledgements

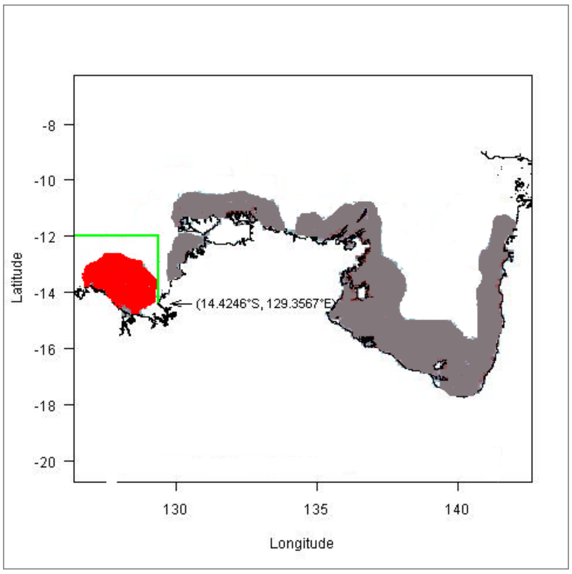
We gratefully acknowledge funding for this project no. 2019/0843 from the Australian Fisheries Management Authority (AFMA) and CSIRO Oceans & Atmosphere. Data provided by Australian Fisheries Management Authority (AFMA) and the NPF Industry Pty Ltd. We would like to acknowledge inputs and feedback from members of the Northern Prawn Fisheries Resource Assessment Group (NPRAG). Sean Pascoe provided helpful input. We are grateful to Rob Kenyon and Tonya van der Velde for reviewing an earlier draft.

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 the White Banana and the 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 hierarchical Bayesian based annual biomass dynamic models (Zhou et al. 2009), 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 of the fishery (Punt et al. 2011). It is possible to apply a size-structured bio-economic model to the Tiger Prawn fishery because there are both survey and bio-economic data available. However there are no fishery-independent survey data and very limited economic information available for the Redleg Banana Prawn fishery and hence a simpler modelling approach is applied. For the Redleg Banana Prawn fishery of the Joseph Bonaparte Gulf (JBG), we apply a production model that represents prawn dynamics on a quarterly time step.

Although fished extensively through southern Asia to East Africa, in Australia, Redleg Banana Prawns are a relatively small percentage of the total NPF prawn catch (between 2011 -2020, Redleg Banana Prawns were 4-17% of the total Banana Prawn catch). Most Redleg Banana Prawns within the NPF are caught in the 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.

Figure 1. The area (red shading) 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.*



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

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. Effort then climbed to 358 boat days in 2013, and to 559 boat days (a 56% increase) in 2014, before decreasing to the lowest level yet of 79 and 76 days in 2015-2016. More recently, effort levels have been variable. Effort was high in 2017 (548 boat days), which corresponded to a period of high prices, but decreased to 213 boat days in 2018 and then down to only 75 days in 2019, before increasing again to 195 days in 2020. Changes in effort over the entire period of the fishery reflect not only prawn catch rates and prices 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 recognized (Plagányi et al. 2020).

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 options, and stakeholders selected a permanent closure of the first fishing season (April-June) 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 a number of implications for the stock assessment arising from closure of the first fishing season, and these have been explored as part of this project. 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 fishery closure years or data-insufficient years it won't be possible to reliably update the assessment model and this project investigated the implications of this change as well as recommendations for defining a data-sufficient year.

The change to the Redleg Banana Prawn harvest strategy also resulted in a number of implications for reference level settings and hence these were reviewed as part of this project and recommendations discussed in consultation with stakeholders. For Redleg Banana Prawns, the LRP proxy of $0.5B_{MSY}$ is used (as per the *Commonwealth Fisheries Harvest Strategy Policy and Guidelines*). The overfishing reference points are the fishing mortality levels that correspond to the above LRP over the long-term. The Redleg Banana Prawn assessment is less certain than the tiger prawn assessment because it lacks independent monitoring surveys, that are available for tiger prawns. The Redleg Banana Prawn LRP therefore does not align with the tiger and endeavour prawn LRP, which are based on the value of the five-year moving average of S_Y/S_{MSY} (where 'S' is stock size). For Redleg Banana Prawns, the LRP is triggered as soon as the stock falls below $0.5B_{MSY}$ for two successive data sufficient years (i.e. two years in a row where sufficient data are available to run the assessment).

2 Needs

The AFMA Commission supported NPRAG and NORMAC's recommendation and decided the Management Strategy Evaluation (MSE) harvest control rule two (HCR-2) (Blamey et al. 2020), which is to close the Joseph Bonaparte Gulf (JBG) during the banana prawn season (1 April – 15 June), in addition to the current rule, should be implemented from 2021. The RAG agreed that the rules identified were the ones to be reviewed and supported a working group of CSIRO, AFMA and NPFI collaborating on a draft harvest strategy that could be considered by the RAG at its May 2021 meeting. The closure of the first season is considered a primary management measure to limit fishing effort, safeguard the spawning stock biomass and yield economic and ecological advantages.

The current Harvest Strategy (HS) for the Redleg sub-fishery has been reviewed and as part of this project, several changes have been proposed and additional data and modelling analyses are being undertaken to refine aspects of the revised and simplified HS (see minutes of NPFRAG May 2021).

Short statement

To better safeguard both the prawn population and the fishers who depend on it, researchers from CSIRO, Australia's national science agency, have worked closely with industry and managers to inform the sustainable and ongoing management of the Northern Prawn Fishery (NPF).

Using an innovative modelling tool the robustness of alternative fishing strategies was tested, the strategy adopted by industry and managers, to provide ecological and economic benefits, is to close the first season (1 April – 15 June) to Redleg Banana Prawn fishing every year.

This research highlights the importance of industry, managers and science collaboration to help with the ongoing management of the NPF, globally recognised as one of the world's best managed fisheries.

3 Objectives

- Re-develop the Redleg Banana Prawn assessment model with focus on meeting the requirement for the current harvest strategy, including refinement of outputs for recommended TAE;
- Investigate adjustment of reference point values to include new information;
- Explore possible correlations between catchability and calendar quarter as well as assumptions and factors affecting availability and how it varies amongst quarters;
- More thoroughly explore the uncertainty associated with the TAE model output as a result of recruitment variability;
- Explore sources of variability in recruitment estimates, such as environmental drivers or possible issues with the assessment model or data; and
- Consider ways of incorporating more information in the assessments, especially that relating to recruitment success. This might include, for example, size information from grade data
- Based on the outcomes of the Redleg MSE project, modify stock assessment model accordingly and ensure it aligns with changes made to the harvest strategy

4 Method

4.1 Minimum Effort (number of boat days) from CPUE data needed (in this case all from the same fishing season rather than two seasons as previously) for these data to be adequately representative and for the stock assessment model estimates to be acceptably reliable

We undertook a number of data and modelling investigations to inform on the minimum number of boat days that could reliably be used to estimate CPUE and hence for input to the stock assessment model. In particular we focused on whether relatively low effort levels were adequately informative and unbiased because the minimum effort level also defines the fishing effort level below which no stock assessment is conducted and hence it needs to be low enough to not substantially impact on the Redleg Banana Prawn population, even in years of low abundance.

We used three approaches to inform our investigations, starting with data analyses and simple model simulations, to more detailed modelling investigations:

First we correlated catch and effort for all years since 2002 to verify whether low effort levels always correspond to low corresponding catches.

We analysed average weekly CPUE and associated standard deviations to obtain the CV (Coefficient of Variation). We plotted the latter as a function of total Effort (boat days) to assess the extent to which the associated variation increased as effort levels are reduced, i.e. at what point the variable becomes unreliable due to the associated variance being too high to be informative.

Second, we ran the stock assessment to compare the effect of using a higher (n<50 boat days per quarter) versus lower (n<20 boat days per quarter; base-case) cut-off rule (Table 1).

Next, we analysed data for the period 2007 to 2010 because this corresponded to the previous period when the first season was closed to fishing, and hence was the most representative of the kind of relationships that might be expected between catch and effort when fishing commenced in the second season as per the recent change to the harvest strategy. We extracted weekly catch and effort data starting from week 31. We then calculated the cumulative effort and catch totals for each additional week's fishing effort. Next we computed the CPUE that would have been estimated had data only been available up until that point, which we term the "partial" CPUE. This was computed by dividing the cumulative catch to that point by the corresponding cumulative effort. For each of the four years, we plotted how CPUE estimates become updated as more data became available. We compared these weekly CPUE estimates with the actual total CPUE estimate based on the full season's fishing. We calculated the percentage difference between the partial-season CPUE and final CPUE by diving the initial estimates by the final estimate.

Based on the data analyses above, we set up three simulations to test the impact on model estimates when CPUE was based on very few, few or low data (see Table 3 for definitions), compared with the data-rich base-case stock assessment model. To keep our simulations as realistic as possible, we used actual partial CPUE estimates corresponding to cumulative effort totals as shown in Table 3, for the period 2007-2010. We used the structure shown in Table 3 to test the impact on model estimates when there is a single or four consecutive data-poor years. In all cases we used the actual total catches so that the model represented how the Redleg population trajectories were likely to have changed in response to actual catches, but we assumed that we had a less reliable CPUE (i.e. the low-data estimates as shown in Table 3) for use as an index of relative stock abundance. We also assumed that there was no index available for the fourth quarter (as is the case in the base-case). Sim1 tests the effect on a single year, sim2 uses CPUE estimates derived from very low data, sim3 from low data, sim 4 from few data and sim5 is a combination that assumes the usual data available for high catch year 2009, and other years CPUE is based on approx. 60-80 boat days only.

In each instance, the model was refitted using the modified CPUE series. From a stock assessment perspective, we assumed a reasonable acceptable error in assessment of the stock status is 10%, noting that more than this risks in particular over-estimating B_{LIM} rule being incorrectly triggered or incorrectly not triggered. The 10% cut-off is consistent with the Commonwealth Harvest Strategy Policy to "maintain all commercial fish stocks, including byproduct, above a biomass limit where the risk to the stock is regarded as unacceptable

(B_{LIM}), at least 90 per cent of the time”. We therefore recommended use of this criterion to guide choice of a suitable data-sufficient number of boat days.

4.2 Minimum data requirements for fishing power analysis updates and pre-agreed approach for using a fishing power estimate based on recent estimates when necessary

A Redleg Banana Prawn stock assessment needs to be conducted annually to inform on stock status. Therefore, a fishing power estimate is required each year. However, it may be possible to align the detailed fishing power analyses with those conducted for Tiger Prawns, for which an assessment is only done every second year; this is also because the Redleg Banana Prawn fishing power model builds on that for Tiger Prawns. Moreover, the additional work required to generate fishing power annually for Redleg Banana Prawns may not be justified. A related question is what to do if there are insufficient data for estimating fishing power in a given year. We did a preliminary evaluation of the potential error if we use an extrapolated fishing power estimate for every second year as input to the stock assessment, and then replace it with a more detailed update every alternate year. The approach therefore used an extrapolation based on the slope of previous 1,3, 5 or 7 years’ fishing power for both odd and even years.

4.3 Consider if possible to drop HS rule: ‘whether or not the average catch per boat per fishing day in August, September & October is 390 kg’

We reviewed the recommendation that this empirical rule be dropped from the revised HS, and discussed our recommendations with the NPFRAG.

4.4 Consider whether changes are needed to the Hockey-stick rule applied to the outputs of the current stock assessment.

So-called ‘Hockey-Stick rules’ are commonly applied harvest control rules that specify a maximum fishing rate which declines linearly once biomass decreases below some pre-specified level, down to a minimum value at some lower biomass cut-off level. The application of a Hockey-Stick rule in the Redleg Banana Prawn HS has been problematic because of challenges regarding changing intra-annual fishing patterns, large uncertainty in the assessment due to relying on CPUE data only, and observed differences between the recommended TAE and actual annual effort. Hence it hasn't been possible to define a constant target fishing mortality proportion 'FTARG' as this has varied depending on the pattern of fishing. However, going forward this process will be simpler because the fishing pattern is now expected to be more constant (restricted to second season only). We therefore reviewed the settings used in the current Hockey-Stick rule and recommended any changes needed to better align the Hockey-Stick rule with the revised Harvest Strategy. We discussed recommended changes at NPFRAG meetings to seek input from stakeholders.

4.5 Investigate adjustment of reference point values considering that all fishing now occurs in a single fishing season only

In consultation with stakeholders, we reviewed the appropriateness of current reference levels used in the Redleg Banana Prawn stock assessment, especially given the major recent change to the fishery related to closing the first season.

4.6 Redleg Banana Prawn CPUE trigger considerations

To inform what average nominal CPUE might usefully inform a voluntary reference level for fishers when fishing performance may be deteriorating towards the end of the fishing season, we drew on the MSE test work of Blamey et al. (2020, 2021) as well as economic considerations, including based on Pascoe et al. (2020).

4.7 Consideration of other data sources

We collated and analysed available additional data sources such as the size grade data to investigate whether these data could be used as inputs to the stock assessment model, or as additional indicators for the fishery. We also considered other sources of data that could be used.

4.8 Based on the outcomes of the Redleg MSE project, modify stock assessment model accordingly and ensure it aligns with changes made to the harvest strategy

The stock assessment model is presented in Appendix 1, together with some notes on modifications being made in response to the revisions to the Harvest Strategy (see also Appendix 2) that were made in response to the outcomes of the Redleg MSE project (Blamey et al. 2020, 2021). Ongoing assessment updates have been presented at NPFRAG meetings throughout the duration of this project, and the forthcoming 2022 assessment will include all final revisions following review by stakeholders.

5 Results and Discussion

The section below summarises results pertaining to some key aspects considered as part of this project. Progress to date on these tasks was reported at the May 2021 NPRAG and February 2022 NPRAG meetings, and copies of the presentations are available on request.

5.1 Minimum Effort (number of boat days) from CPUE data needed (in this case all from the same fishing season rather than two seasons as previously) for these data to be adequately representative and for the stock assessment model estimates to be acceptably reliable.

Preliminary data investigations

Preliminary investigations suggested there is a highly significant ($p<0.01$) correlation between Catch and Effort (Figure 2A-C). This suggests that if fishing effort is low in any year, then total catch will almost certainly be low and hence for low effort years, there is some confidence that associated catches will be sufficiently low that they will not add greatly to the total stock mortality for that year. Low fishing effort in the JBG is often driven by the opportunity costs of fishing in alternative areas with more favourable catch rates and prices (Pascoe et al. 2020).

For data over 2002 to 2020, the average weekly CPUE was used to calculate Quarter 2 and Quarter 3 averages and associated standard deviations to obtain the CV (Coefficient of Variation) which is plotted as a function of total Effort (boat days) for corresponding quarters (Figure 3). Although the CV associated with CPUE values in low effort years was expected to be higher than for years with more data, no clear trends were obvious, suggesting CPUE is highly variable even under large effort scenarios (Figure 3).

Using data since 2000 (i.e. restricting to a period of fairly comparable effort levels), there was a weak positive correlation between the second season and first season nominal CPUE (Figure 4; $p<0.05$). Whilst further work is required to verify, if relative stock abundance between seasons is related (e.g. due to some underlying mechanism), then losing the Quarter 2 CPUE information may not substantially deteriorate model performance as the stock dynamics will still be captured.

Weekly average CPUE data for the second season for recent years 2011 to 2020 were also analysed to investigate intra-annual trends in these data (Figure 5). This suggested that CPUE is highly variable over time but in general there is a decrease in CPUE over the season. This analysis should ideally be redone to take into account neap tides given that fishing takes place during neap tides (Plagányi et al. 2020). Analyses of these data also suggest that it may be preferable to continue to separately fit to Quarter 4 data when there are sufficient data in a year. Based on Figure 5, the CPUE in the fourth quarter is generally lower given the decline during the third quarter, but a moderately high CPUE is maintained in the fourth quarter in some years of high abundance and declines steeply in other years and hence may provide a valuable additional check as to stock status at the end of the fishing season. This was particularly evident in 2014 when the reasonably high Quarter 4 CPUE suggested that the low abundance in 2015 was more likely due to environmental and other factors than to overfishing (although some overfishing may have occurred as the 2014 effort levels were higher than the target effort levels). We note that fishery dependent CPUE data are inherently difficult to interpret as there is confounding with fishing operations, and they are not a standardised survey of relative abundance of prawns.

Stock assessment minimum data cut-offs

The May 2021 Reference Case assessment, applied the following rules (Plagányi et al. 2021):

1. Require total annual Effort (boat days) >= 75 in current assessment year
2. Minimum quarterly total boat days = 20 for each of Quarters 2 and 3 data, to be included in the assessment
3. Minimum quarterly total boat days = 10 for Quarters 1 and 4 data to be included in the assessment

Application of the data rules in the assessment resulted in excluding the following CPUE data from the model fitting process: 2010 Quarter 4; 2013 Quarter 4; 2015 Quarter 3; 2018 Quarter 4; 2019 Quarters 3 and 4; 2020 Quarter 4 (Table 1).

The stock assessment was rerun to compare the effect of using a higher (n<50 boat days per quarter) versus lower (n<20 boat days per quarter; base-case) cut-off rule (Figure 6). Results suggested that having fewer data can noticeably impact both the accuracy and precision of model estimates (Figure 6; Table 2). This aspect required further investigation because the data rules assumed that data would be available for both the first and second season, whereas with effect from 2021, data for this fishery will only be available for the second season. Further results as described in the next section were thus presented at the February 2022 NPFRAG meeting to inform final choice of a minimum number *nmin* of boat days that can be used to define a data-sufficient year.

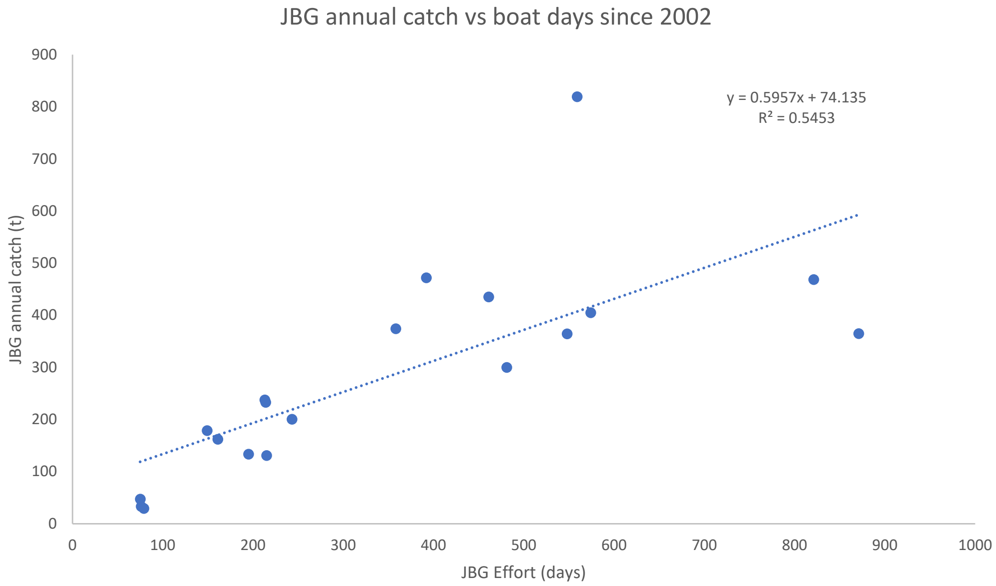
Table 1. Minimum Data Cut-Off Alternatives being considered for use in deciding whether CPUE data considered useful to inform stock assessment. Note that for 2015 and 2016 the stock assessment was run retrospectively as data were available for 2017. **Data less than 5 boat days are not shown due to confidentiality agreement.**

	Boat days per quarter		
	Q2	**Q3**	Q4
2009	0	289	103
2010	0	197	17
2011	84	229	148
2012	22	107	20
2013	233	124	
2014	216	299	44
2015	73	6	0
2016	52	24	0
2017	80	363	105
2018	103	105	
2019	72		
2020	147	39	9

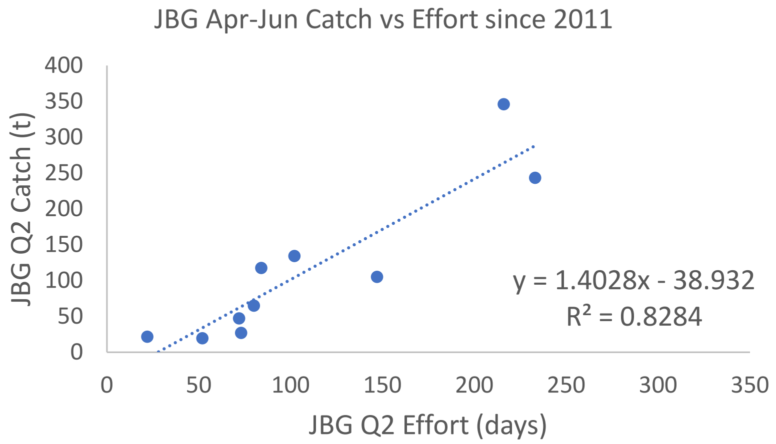
<=5
<20
<30
<50

Figure 2. Correlations of (A) total annual JBG catch (t) since 2002, (B) Quarter 2 total catches since 2011, and (C) Quarter 3 annual catches since 2011 versus the corresponding JBG effort (boat days). The fitted R^2 values show the proportion of variation in catch that is explained by effort.

(A)



(B)



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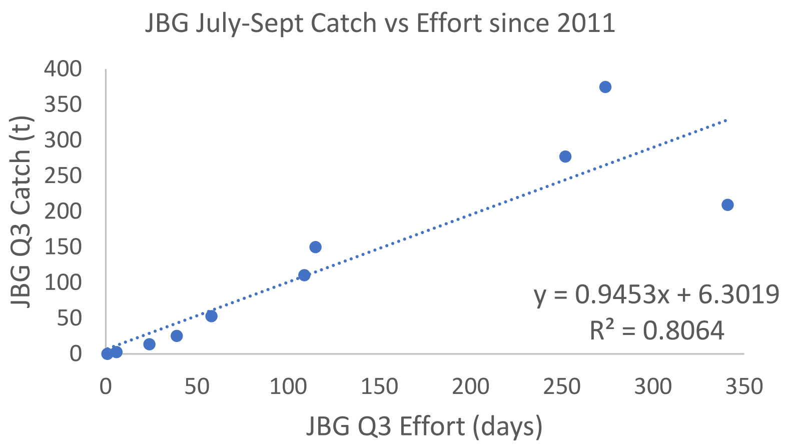
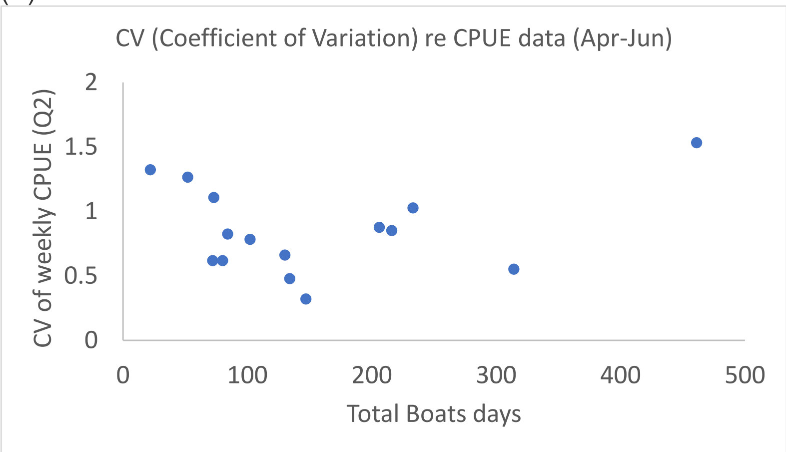


Figure 3. Plots showing the Coefficient of Variation (CV) associated with decreasing levels of effort (total boat days) for (A) Quarter 2 and (B) Quarter 3 of Redleg Banana Prawn fishing in the JBG.

(A)



(B)

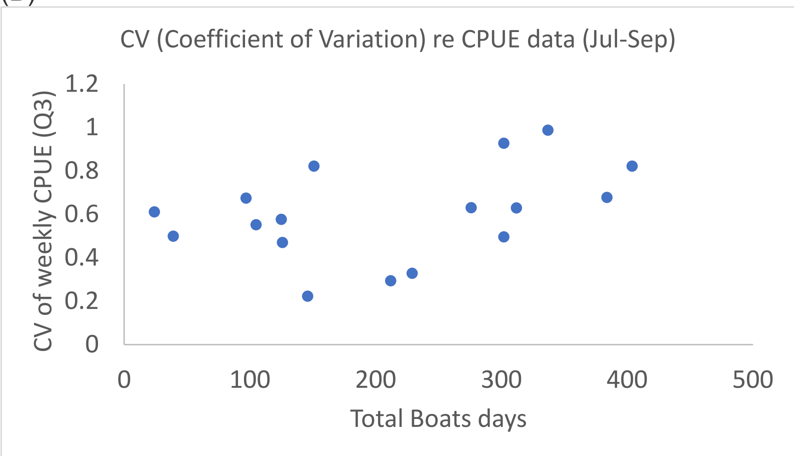


Figure 4. Correlation between the second and first season nominal JBG Redleg Banana Prawn CPUE for all years since 2000 for which there were sufficient data.

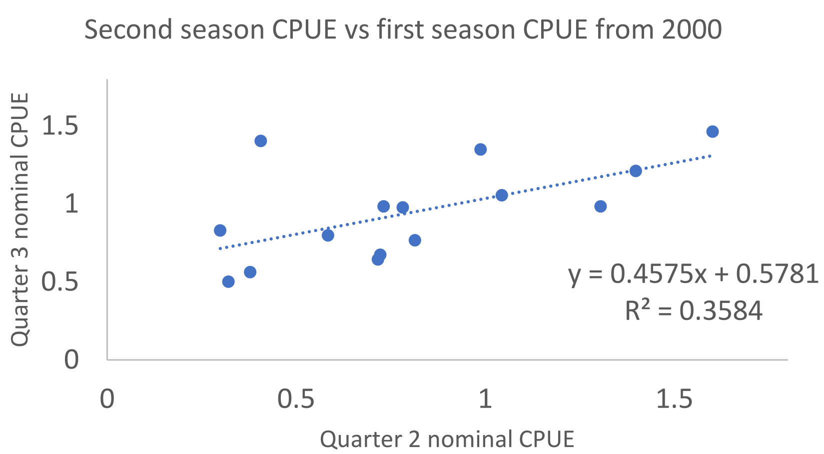


Figure 5. Patterns for years 2011 to 2020 in weekly average CPUE (ignoring errors for ease of viewing) shown for weeks 31 to 47.

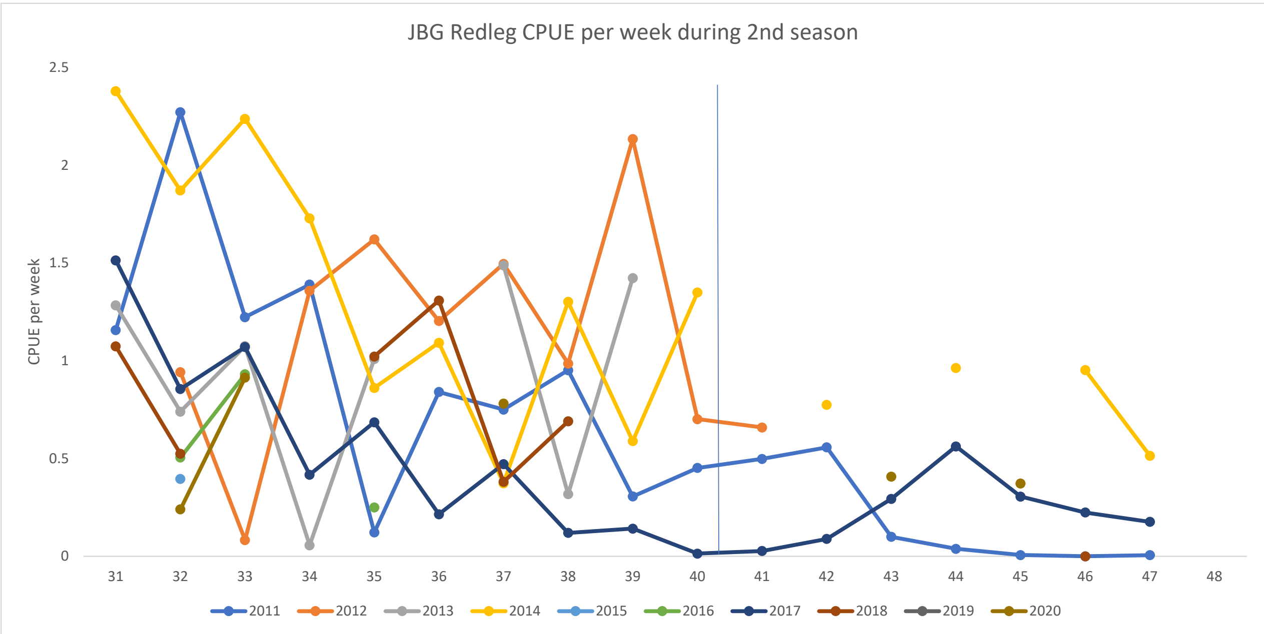


Figure 6. Total annual spawning biomass (t) trajectory using the Base Case model compared with an alternative using a different data rule, namely at least 50 boat days per quarter, for 1980 to 2020. The plot also shows the target spawning biomass level (B_{MEY}), the biomass level corresponding to Maximum Sustainable Yield (B_{MSY}) and limit reference level (B_{LIM}).

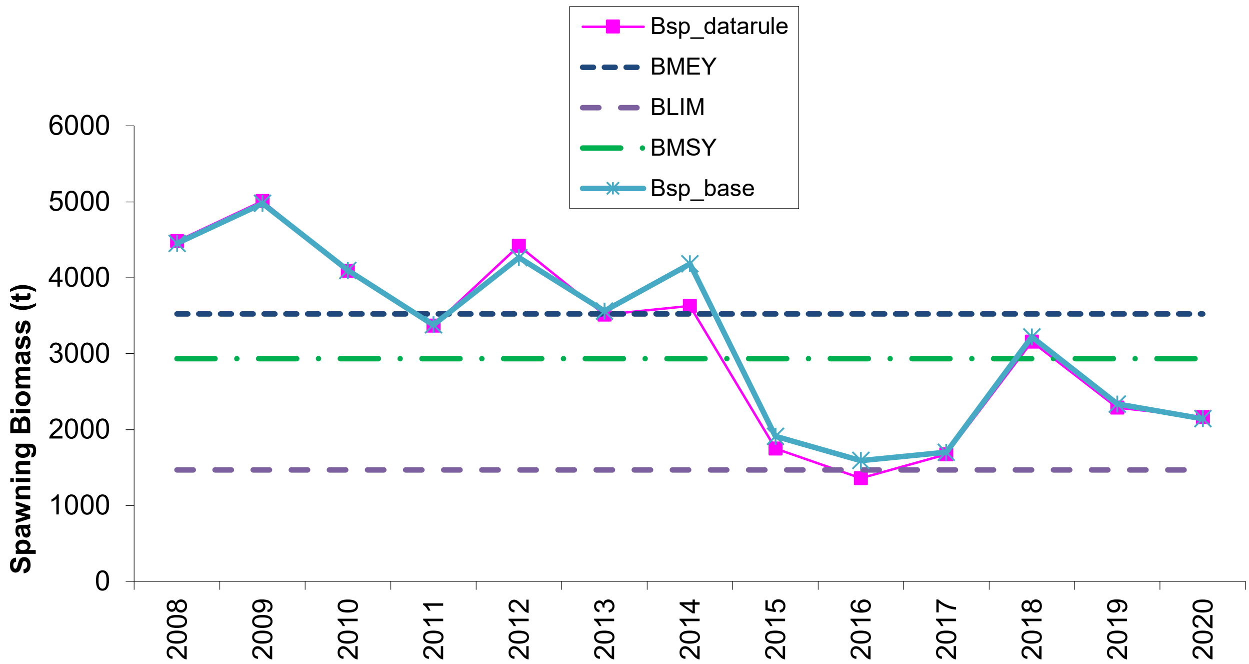


Table 2. Summary of Reference Case model parameter estimates and sensitivity analysis with higher exclusion limit (number of boat days required to incorporate CPUE data in model n=50 as opposed to n=20 in the Reference Case model).

	(A) Reference Case (sigma 0.8) (n=20)				(B) Data Rule with higher exclusion limit (n<50)			
K_{1980}^{sp}	6316				6405			
Availability during each quarter for period 1980-1988,	1.00	0.64	0.80	0.66	1.00	0.64	0.80	0.66
Availability during each quarter for period 1989-2006,	0.00	0.78	1.00	0.58	0.00	0.77	1.00	0.56
Availability during each quarter for period from 2007-2010	0.00	0.00	1.00	0.58	0.00	0.00	1.00	0.56
Availability during each quarter for period from 2011	0.00	0.98	1.00	0.58	0.00	1.00	1.00	0.56
Catchability – *q*	2.4E-04				2.5E-04			
-lnL:overall	-69.8				-64.2			
Observation error variance,	0.30				0.30			
Current depletion - $B_{sp}(2020)$ relative to B_{1980}	0.34				0.33			
No. parameters	50				50			
AIC	-39.514				-28.416			

Retrospective analysis of CPUE data over 2007-2010

The Redleg Banana Prawn partial CPUE estimates were seen to become rapidly updated as fishing progresses through the season (Figure 7). The high CPUE year 2009 (which had a total catch of 472t) showed the most variability with the first week underestimating CPUE fairly substantially and the second week over-estimating CPUE before estimates started converging towards the actual average value that is considered a more reliable indicator of the underlying stock biomass. Note that the slight downward trend is to be expected given depletion due to fishing through the season. The low CPUE year 2007 (which had a total catch of 131t), showed less variability initially and increased slightly late in the season such that the early CPUE estimates slightly under-estimated the actual average CPUE (Figure 7A). After the first two weeks of fishing, the percentage difference between the partial and actual CPUE mostly decreases to less than 25% (Figure 7B). We note that the analysis has assumed a normal error distribution and the CPUE calculation is done at the level of week (across fishing vessels) and not per vessel per day, the analysis could be repeated assuming asymmetric errors and a different CPUE calculation which might yield greater errors.

For 2007, the percentage error only reduces to less than 10% when the number of boat days exceeds 91. For 2009, a year with a high total catch of 472 t, the CPUE estimates only start decreasing to the final lower average estimate once the number of boat days exceeds about 233 days. We note the focus of the current project is whether CPUE estimates based on few data in years of low stock abundance, such as 2007, can 1) reliably inform on the underlying stock abundance and 2) whether the corresponding catches are considered low enough that fishing pressure is not assessed to have a significant impact on an already low stock. We reiterate that we acknowledge that low Redleg Banana Prawn fishing effort in a year may be due to other factors as well, and in particular economic factors (Pascoe et al 2020). The year 2008 also had a relatively low total catch of 162t but CPUE was above average. In this case, the pattern of the partial CPUE initially was higher than the final estimate. It then decreased towards the final estimate once effort exceeded about 100 boat days, suggesting that the partial estimates did a reasonably good job at estimating CPUE had fishing ceased at that point. Finally, 2010 had a total catch of 233t, and above average CPUE, with initial partial CPUE differing by about 10% from the final value, converging once the number of boat days exceeded about 100.

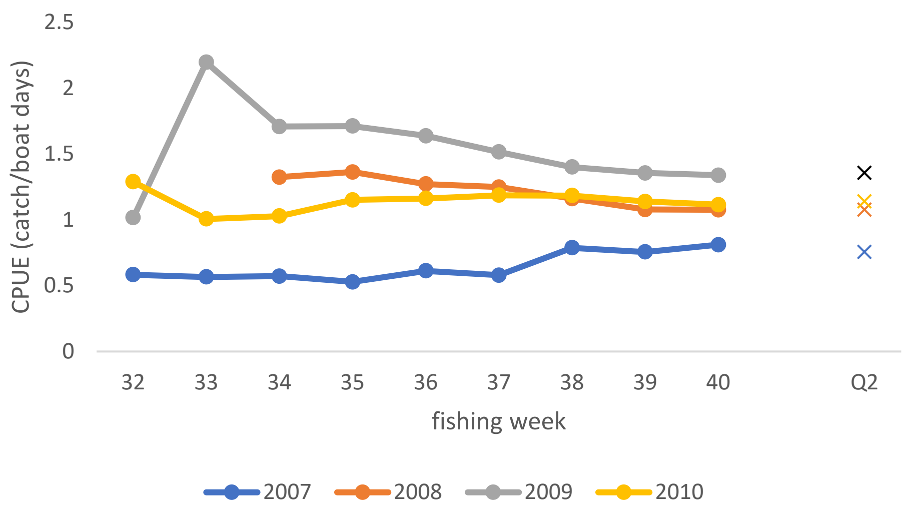
Using the data for 2007-2010, (and using a cut off value of effort = 125 boat days to expand differences at low effort levels), we plotted the CPUE percentage errors as a function of the fishing effort up until that point (Figure 8). This suggested that there was a fairly even spread in the relative errors corresponding to low fishing effort levels and hence that while the precision of the CPUE estimates decreases at low effort, there was no clear direction of bias (i.e. the CPUE estimates are biased but not clearly in one direction).

We used the same data sub-set to analyse the relationship between the "partial" catch (i.e. total of catches up until a particular week corresponding to a cumulative effort total as shown) and the fishing effort level (Figure 9A). Using data from 2000 to 2020, we computed the median catch, effort and CPUE values which were 288t, 363 boat days, and 0.63 t/boat day respectively. The averages were similar to the median values. We also computed two illustrative lower catch levels corresponding to 50% and 25% of the median values, yielding estimates of 72t and 144t respectively. We superimposed the low catch total of 72t on Figure 3 and highlighted that total catches were less than this level for a corresponding number of boat days less than about 60.

As a further check of the "cut-off" fishing effort level at which corresponding catches can be expected to be very low, we repeated our analysis using all data for the second subset of years 2011 to 2020, and showing only values with cumulative effort less than 100 boat days (Figure 9B). As can be seen from Figure 9B, the corresponding total catch is very low for effort levels less than 50 boat days (<25% of the median catch), and is low for effort levels less than about 85 boat days (<50% median catch).

Figure 7. (A) Comparison of how Redleg Banana Prawn nominal CPUE estimates become successively updated as fishing progresses through the season, approaching the actual final estimate shown with an X, for each of the years 2007-2010 when fishing only commenced in the second season. (B) plot with the CPUE estimates divided by the final nominal CPUE estimate to show the percentage difference in these estimates over time, as well as the point at which these differences become less than a 25% difference.

(A)



(B)

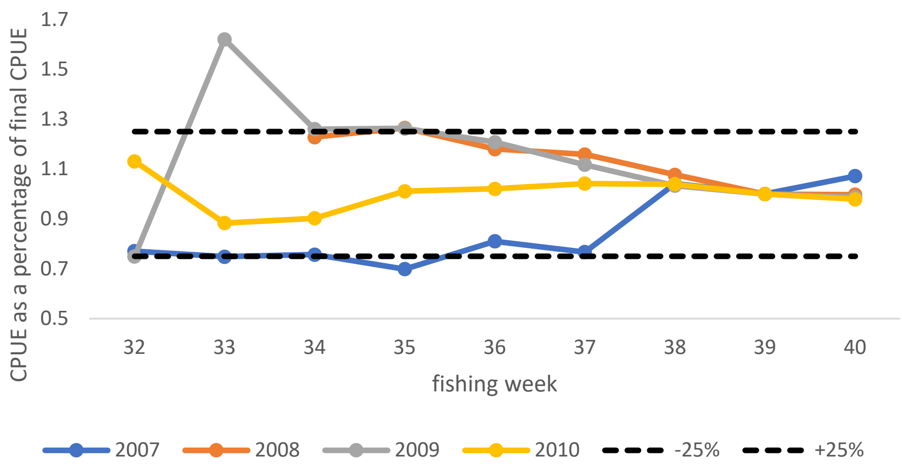


Figure 8. The partial CPUE as a percentage of the final CPUE, plotted as a function of the corresponding fishing effort level (boat days) used to calculate the partial estimates.

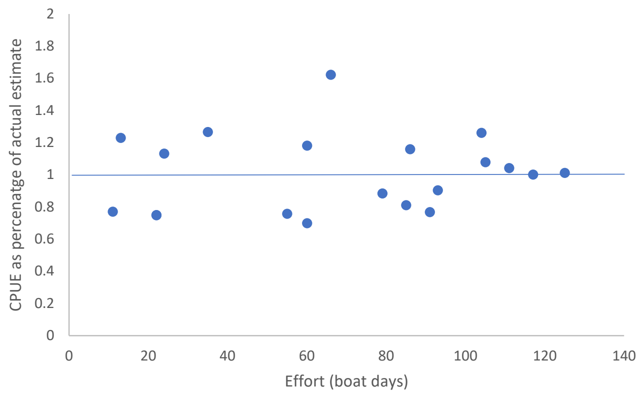
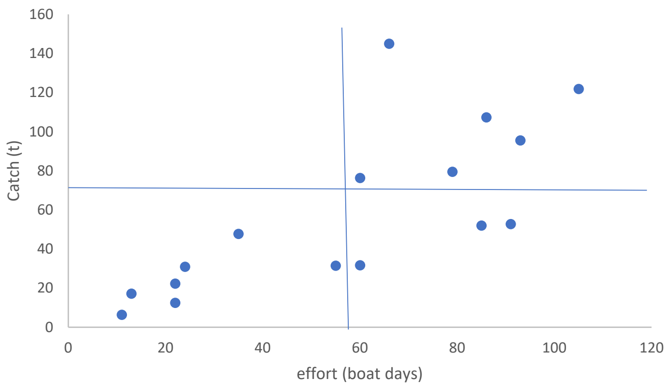
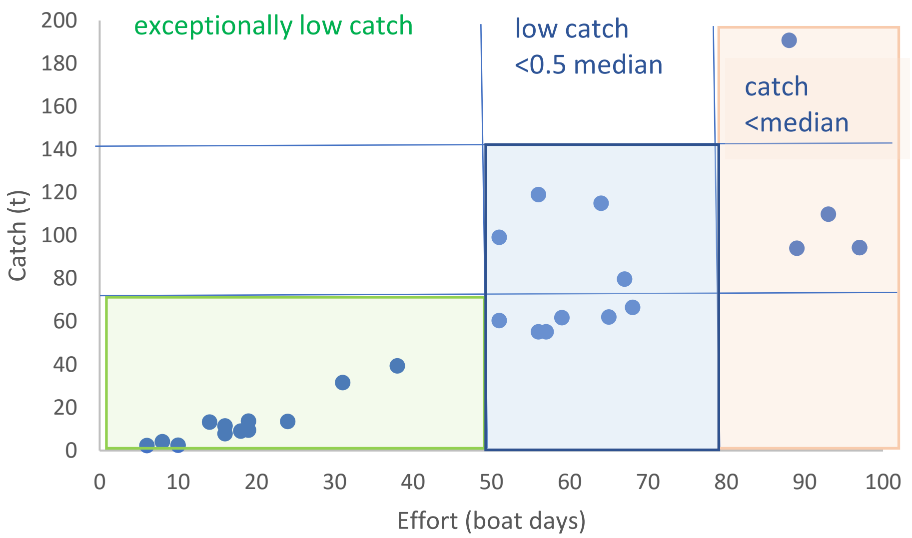


Figure 9. Plot of the catch corresponding to cumulative effort levels (boat days) as shown when using the data for (A) 2007-2010 and (B) 2011-2020. See text for details

(A)



(B)



Retrospective model simulations to inform choice of data-sufficient number

The model-estimated spawning biomass (B_{sp}) and commercially available biomass (B_{comm}) relative depletion estimated for each year when using the Reference Case model compared with the alternative simulations are presented in Table 4. The differences in these depletion estimates are translated into percentage errors in Table 5 for comparison with the criterion that errors in the stock assessment status of the resource should be 10% or less. Sim1 shows that the use of an inaccurate CPUE in one year has only a negligible effect on the estimation of stock status the following year because the stock is short-lived and highly variable, and the model is refitted each year with the new year's data. The use of inaccurate CPUE values is seen to result in either an over- or under-estimate of the stock abundance in a given year. The relative errors are similar under sim2 and sim3, hence when using very low data or low data (see Table 3). However, the errors reduce substantially in sim4, which assumes there are slightly more data available. Sim5 shows the results of a combination scenario that assumes there are between 60-80 boat days available. This last scenario has been tuned to roughly achieve percentage errors of 10% or less. This wasn't strictly possible for low abundance year 2007 because the CPUE only increased to be more similar to the final average value once the cumulative boat days reached 111 days.

When evaluating the effect on the overall model likelihood of the alternative simulations, there was a relatively small deterioration in the quality of the overall fit when only a single year's CPUE estimate was inaccurate (-lnL=-69.8 (base) vs - -67.8 (sim1)). However, there was a much larger deterioration in the negative log likelihoods under sims 2-4 (ca. -65). Simulation 5 resulted in less of a deterioration in model fit (-lnL = 67.1). The fits to the Quarter 3 CPUE data are shown in Figure 10. There are also some substantial differences in the stock-recruitment residuals estimated for the years using the inaccurate CPUE estimates. However, these are more satisfactorily under sim5, with Figure 11 comparing the estimates and associated Hessian-based standard deviations.

Considering these results as well as the catch-effort relationship shown in Figure 9, suggests that to ensure the stock assessment outputs are adequately reliable (using our definition of an acceptable error being 10% or less), the data-sufficient "cut-off" number below which we advise a stock assessment should not be conducted should be in the range 60-80 boat days, and sim4 (based on 85-104 days) suggests at the upper end of the range. From a practical perspective, the total number of annual boat days for the Redleg Banana Prawn fishery has only dropped below 100 three times as follows: 2015: 79d.; 2016 76 d.; and 2019: 75 d. Historical effort suggests that there is a low probability of the data-sufficient “cut-off” being triggered (i.e. historically a non-assessment year would never have been triggered) and supports setting this number at around 70 days, given there is a precedent for this. Using fewer data would mean the stock assessment outputs become considerably less reliable in a year, and fishing power may not be estimated for that year (e.g. if the model in unable to converge). Note that in the analyses described above, we assumed that the fishing power estimates used to standardise interpretation of the CPUE as an index of abundance remained as previously and hence did not account for potential errors in the fishing power estimates which would likely have occurred with very few data – or indeed the fishing power model may not have been able to converge when the number of boat days was less than 70 (the historical precedent) such that an extrapolated value would have been substituted, further compounding errors and potentially introducing bias under low data scenarios.

The analyses suggest that if fishing effort (boat days) is less than about 80 days, the corresponding catches are likely to be very low and therefore not pose much additional risk to the stock. Catches for these low effort levels are likely to be less than half the median catch. For this highly variable stock, when the biomass is at the target level the catch is likely to be approximately at the median level. Hence reducing the catch to half of median is a substantial decrease in catch. This low level of catch might be recommended by a Hockey-Stick type control rule when stock abundance is estimated to decrease. Nonetheless, if there are any substantial increases in fishing power or other changes in the fishery compared with past performance, then these thresholds should be reviewed.

A final consideration relates to any trade-offs with respect to deteriorating model fit and predictions due to not running an assessment in some years or having data gaps. To investigate the effect of data gaps on modelling outputs, additional simulations were run which assumed either a single data-gap year of 2007, or two consecutive data-gap years (2007-2008) and finally three consecutive data gaps years (2007-2009). As illustrated for the last scenario in Figure 12, this means that the model is not fitted to CPUE data in some years and it also results in an increase (i.e. deterioration) in the total negative log likelihood Table 6. However as shown in Table 6, there is a minor effect on the model estimate of stock status in the year following the data gap, i.e. when reliable data are again available to inform the model. Hence due to the short-lived highly variable nature of the Redleg Banana Prawn, it is possible to reliably estimate the stock status following a period with no or few data. The model will still estimate stock biomass in the "missing years", and as can be seen in Table 6.

These estimates are not reliable as no-data years are very different to those year estimates based on actual data – this is because there is no basis to inform the model on likely levels of abundance in the no-data years. These simulations are more extreme examples than are likely in practice because the model applies large catches in those years, whereas no-data or few-data years has in the past corresponded to much lower catches and in that case would likely reduce the disparity between with-data and without-data model versions.

Although the model should be used with caution to make predictions if fitted to CPUE data based on only a few boat days in any year, the results may be useful in informing on the likely past trends in the stock. Previous analyses have shown that if the CPUE estimates based on few data are used in the model retrospectively, the outcomes are an improvement on the no-data estimates shown in Table 6. Retrospective estimates when fitted to low-data CPUE years are less reliable than data for other years and it may be advisable to downweight these low-data CPUE values when fitting the model. A simple downweighting factor (applied only to data-insufficient years, the number of days required for reliable stock assessment) would be to use the number of boat days as a proportion of the median number of boat days over 2000 to 2020 (363 boat days). A low number of days are however unlikely to be sufficient for fishing power estimates given an expected large associated error with those estimates and a risk of introducing bias (due to a very limited 'survey' of the fishery in such a year), and assuming no change to relative fishing power for a very low data year, potentially with a large associated error, would be the usual approach. If the subsequent year has sufficient data to reliably estimate relative fishing power this will help to anchor the time series.

We compared the 2015 model biomass estimate from Plagányi et al. (2016) to that for 2015 in the latest assessment (Plagányi et al. 2021). The initial 2015 biomass estimate is over-estimated (Figure 13), however is within the error bounds of the more recent estimate for 2015 (model with data up to 2021). The fishing power model also converged under past scenarios as follows: 2015: 79d.; 2016 76 d.; and 2019: 75 d.

In summary, when aiming for a maximum error of around 10% in the stock assessment model estimate of stock status, and considering the trade-offs in selecting a data sufficient cut-off number to trigger a change to the need to conduct an annual assessment, we recommend between 60-80 boat days, and towards the upper end of this range. The recommendation is based on past fishery performance (and simulations 4, 5) (Table 5), and we note there is a precedent for using around 70 boat days.

Table 3. Summary of alternative retrospective simulation tests. The table shows the decrease in error of the CPUE estimate [(Cpueref-CPUEsim)/CPUEref x 100] as the number of boat days (i.e. the available data with which to compute the CPUE) is increased.

	Reference Case	Simulation 1 (22 boat days)	Simulation 2 (22≤boat days≤35)	Simulation 3 (55≤boat days≤79)	Simulation 4 (85≤boat days≤104)	Simulation 5 (combination)
		Single low data yr	Very few data cf 30 days	Few data cf. 70 days	Low data cf. 90 days	25% error scenario
2007	215 d.; 0.755	22 d.; 0.565 (25% error)	22 d.; 0.565 (25% error)	55 d.; 0.572 (24% error)	85 d.; 0.612 (19% error)	85 d.; 0.612 (19% error)
2008	161 d.; 1.075		35 d.; 1.362 (27% error)	60 d.; 1.272 (18% error)	86 d.; 1.248 (16% error)	60 d.; 1.272 (18% error)
2009	392 d.; 1.355		22 d.; 1.015 (25% error)	66 d.; 2.196 (62% error)	104 d.; 1.708 (26% error)	*High catch yr so ignore*
2010	214 d.; 1.138		24 d.; 1.288 (13% error)	79 d.; 1.006 (12% error)	93 d.; 1.027 (10% error)	79 d.; 1.006 (12% error)

Table 4. Summary of the model-estimated spawning biomass (B_{sp}) and commercially available biomass (B_{comm}) relative depletion estimated for each year as shown when using the Reference Case model compared with the alternative simulations as shown.

		$B_{sp}/B_{sp}(1980)$				
	Reference	sim1	sim2	sim3	sim4	sim5
2007	0.60	0.48	0.49	0.49	0.51	0.51
2008	0.70	0.69	0.78	0.77	0.76	0.76
2009	0.78	0.78	0.57	1.02	0.84	0.78
2010	0.64	0.64	0.68	0.62	0.61	0.59
2011	0.53	0.53	0.54	0.53	0.53	0.53
2012	0.67	0.67	0.68	0.67	0.67	0.67
		$B_{comm}/B_{comm}(1980)$				
	Reference	sim1	sim2	sim3	sim4	sim5
2007	0.43	0.34	0.34	0.34	0.36	0.36
2008	0.52	0.52	0.58	0.58	0.56	0.57
2009	0.60	0.60	0.43	0.78	0.64	0.60
2010	0.48	0.48	0.51	0.45	0.44	0.43
2011	0.59	0.59	0.60	0.59	0.59	0.59
2012	0.73	0.73	0.73	0.73	0.73	0.73

Table 5. Summary of the percentage error [(B_{sp}_ref-B_{sp}sim)/B_{sp}_ref x 100] in the model estimated spawning biomass in each year using the alternative simulations and relative to the Reference Case. Acceptable errors are defined as those with approximately 10% or less difference compared with the Reference values.

	sim1	sim2	sim3	sim4	sim5
2007	21%	21%	20%	17%	16%
2008	1%	-11%	-11%	-8%	-10%
2009	0%	29%	-30%	-6%	0%
2010	0%	-6%	6%	8%	9%
2011	0%	-1%	0%	0%	0%

Table 6. Summary of the model-estimated spawning biomass (B_{sp}) relative depletion estimated for each year as shown when using the Reference Case model compared with the alternative simulations as shown. The crosses highlight instances where the retrospective estimates of stock status are wrong (because there were no data to inform estimation) compared with the red ticks highlighting where either the retrospective or current year's estimate is reasonably accurate once the model is again fitted to available data.

	Bsp/Bsp(1980)			
	Reference ("correct" depletion)	No_assess_2007	No_assess_2007_08	No_assess_2007_09
2007	0.60	0.84 ✗	0.85 ✗	0.84 ✗
2008	0.70	0.73 ☑	0.90 ✗	0.88 ✗
2009	0.78	0.78 ☑	0.80 ☑	0.86 ✗
2010	0.64	0.64	0.65 ☑	0.65 ☑
2011	0.53	0.53	0.53	0.54 ☑
2012	0.67	0.67	0.00	0.67
-lnL:overall	-69.8	-67.5	-65.1	-62.9

Figure 10. Comparison of the model fits to the Quarter 3 CPUE (standardised after applying fishing power) when using the Reference Case and sim2 (very low data), sim3 (low data), sim4 (few data) and sim5 (combination) (see Table 3). The simulation examples use a reduced number of boat days to compute CPUE in each of the years 2007 to 2010, and the model fits to these low-data CPUE values assuming they are accurate indicators of the relative abundance of the stock. Note that the examples shown have all applied the Reference Case fishing power estimates, but under some low-data scenarios, the fishing power model may not have been able to converge or the outputs would also be less reliable, further compounding errors in the CPUE the model is fitted to.

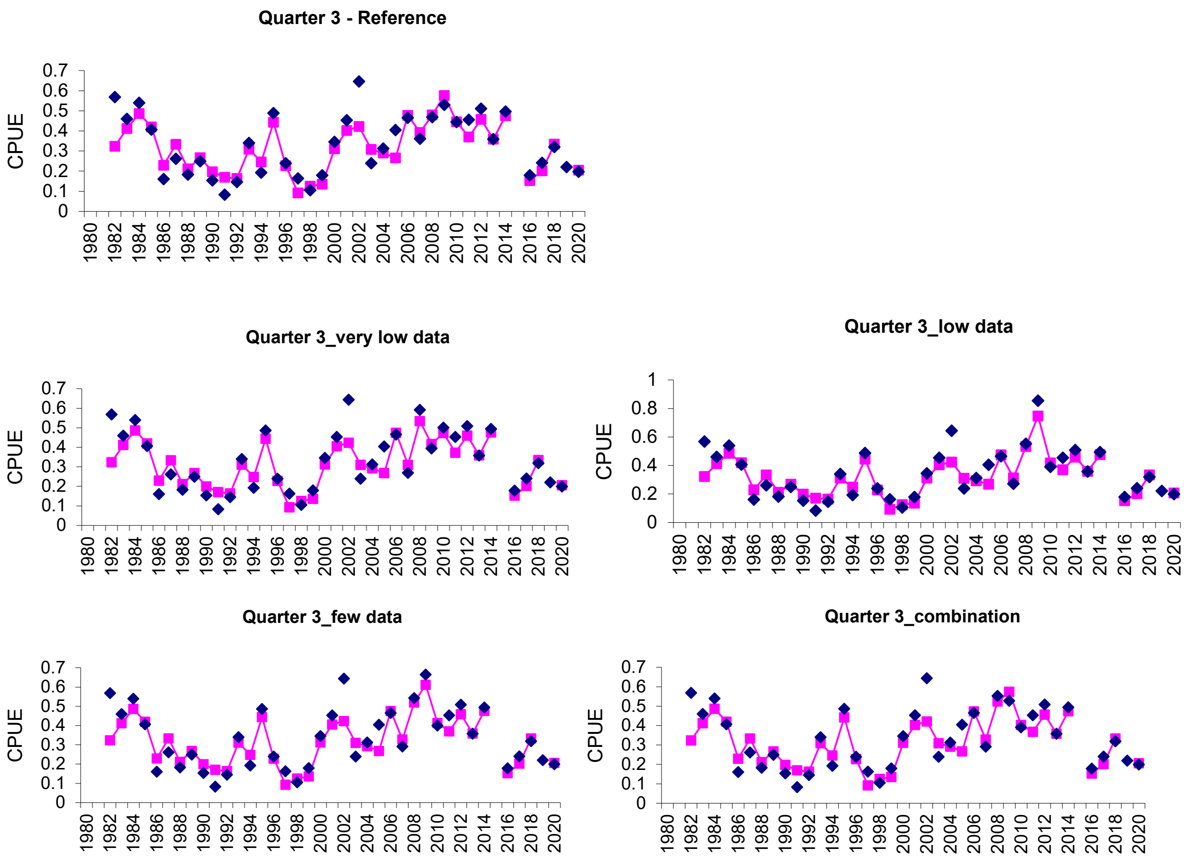


Figure 11. Comparison of the Reference Case and Simulation 5 model estimated residuals (and associated standard deviations) for each of the years as shown. The model shows reasonable similarity between the estimated residuals and standard deviations, whereas larger deviations are evident under the scenarios with fewer data. This is because of increasing differences between the CPUE value based on few data compared with the more representative Reference Case value.

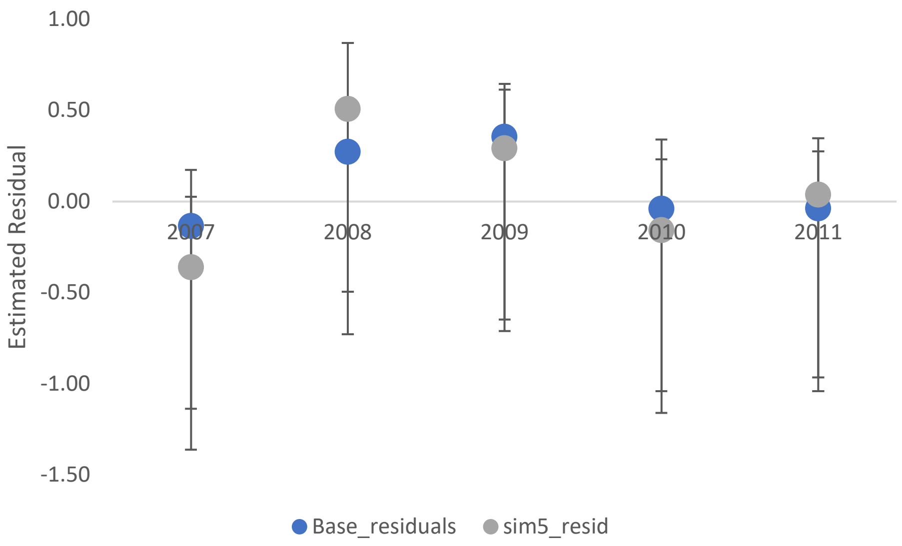


Figure 12. Comparison of the model fits to the Quarter 3 CPUE when using the Reference Case and a scenario with three years' (2007-09) missing data. The plot shows that the model adequately starts refitting to available data once more data become available because the stock is variable and short-lived.

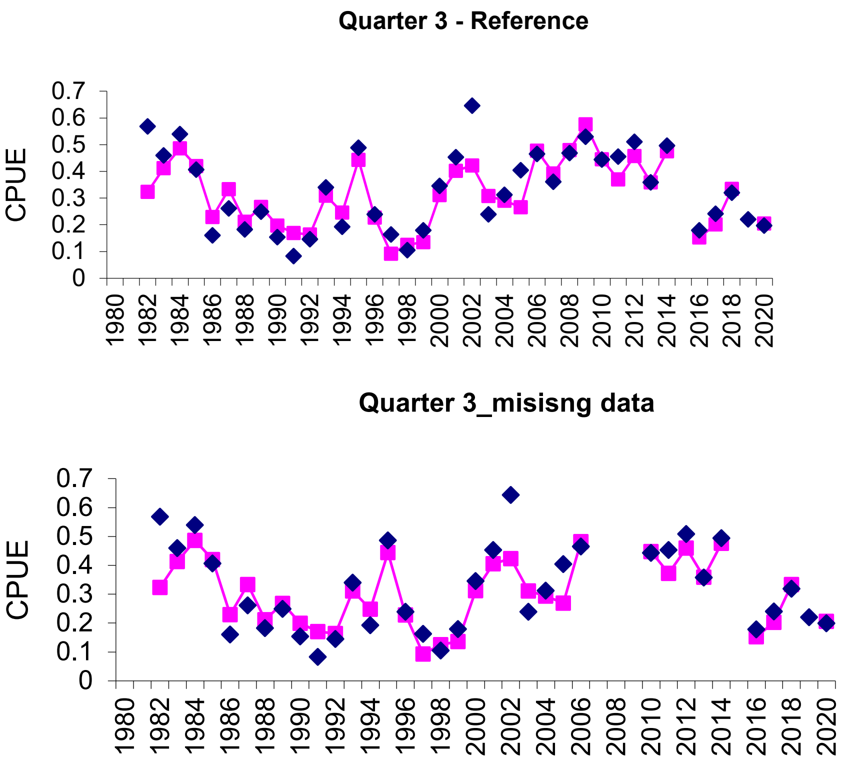


Figure 13. Comparison of the model-estimated 2015 spawning biomass estimate at the time (based on only 79 boat days only) (from Plagányi et al. 2016) with the most recent (stock assessment model (based on data up until 2021 – Plagányi et al. 2021) to show the updated retrospective estimate of spawning biomass. The recent assessment is cropped at 2015 to highlight the comparison.

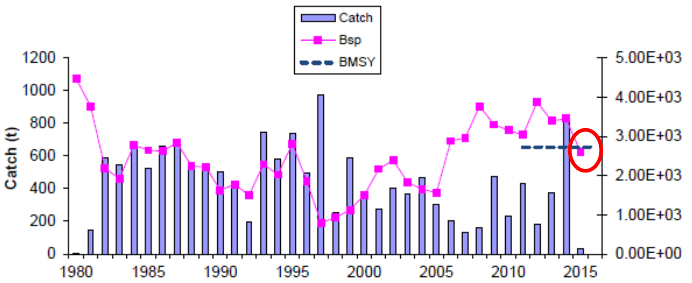
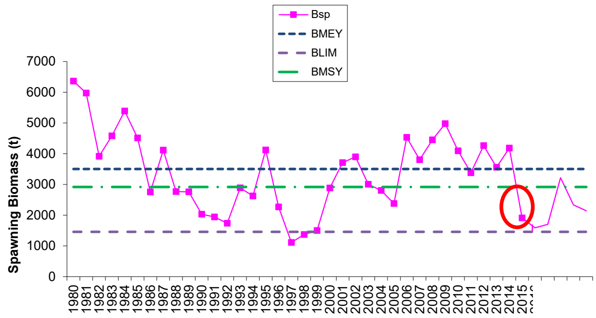


Figure 11. Total annual spawning biomass trajectory using the Base Case model, with total annual catches for 1981 to 2015 plotted as bars, and preliminary spawning biomass as a solid line. The dashed line shows the B_{MSY} computed using the recent average fishing pattern.



2021 assessment cropped at 2015

5.2 Minimum data requirements for fishing power analysis updates and pre-agreed approach for using a fishing power estimate based on recent estimates when necessary

The results when using an extrapolation based on the slope of previous 1,3, 5 or 7 years' fishing power for both odd and even years are shown in Figure 14 and Figure 15.

These analyses suggested bias was introduced using this method for filling in a 'missing' estimate, with the magnitude of bias depending on what year the fishing power estimate was assumed, and the number of preceding years averaged. The bias can be explained by the trend in relative fishing power which is a non-linear increase over time. As new gear and technology are adopted by the fleet there is a step-wise increase in the estimated relative fishing power. Preliminary analyses for the most recent year (2020) suggested this may not make a large difference to the stock assessment predictions (e.g. if there is a small bias it will be swamped by the much greater uncertainties in the assessment due to relying on CPUE data only) but this aspect will nonetheless be explored further.

Under 'low data' conditions, the main concern from a fishing power perspective is related to bias and hence retrospective testing will be done to check how well the model performs (e.g., any systematic changes in residuals) as available data are reduced: this will help inform lower data limits for fishing power analysis. For recent years with notably fewer fishing days (2015, 2016 and 2019) examination of the model diagnostics showed the harvest model residuals were randomly distributed, the model fits were gauged to be reasonable. The fishing power estimates were therefore included in the series, and noting the associated error is larger given substantially less data points. A plot showing a skewed distribution of residuals for the model would indicate poor model fit and potentially biased estimates. If the fishing power model does not converge or the residual plots show a poor model fit, then assuming no change to relative fishing power for a very low data year, potentially with a large associated error, would be the usual approach. If the subsequent year has sufficient data to reliably estimate relative fishing power this will help to anchor the time series.

Note that the fishing power analysis uses the entire year's data when fishing occurred in both seasons so previously this was less of a problem in the low data years. Model diagnostics are in any case used to test the fit. But fishing power also has a season effect incorporated (where season 1 in the model is defined as months 4-8, and season 2 is months 9-12), so the analysis will lose some information with the change to zero effort in the first fishing season (01 April to 15 June) – there is however a long time-series plus a precedent for a first-season closure.

Finally, there might be issues if there are substantial changes in how the industry fishes in the second season: for example, if there is an initial burst of effort as the season opens, or a lag before fishing starts. Future work could explore this effect if realised, for example one aspect would be to reconsider whether a fleet aggregation term, like local effort used in the tiger fishery, could apply.

Figure 14. Preliminary simulations to explore the optimal method for estimating fishing power every second year and extrapolating the value in every odd year.

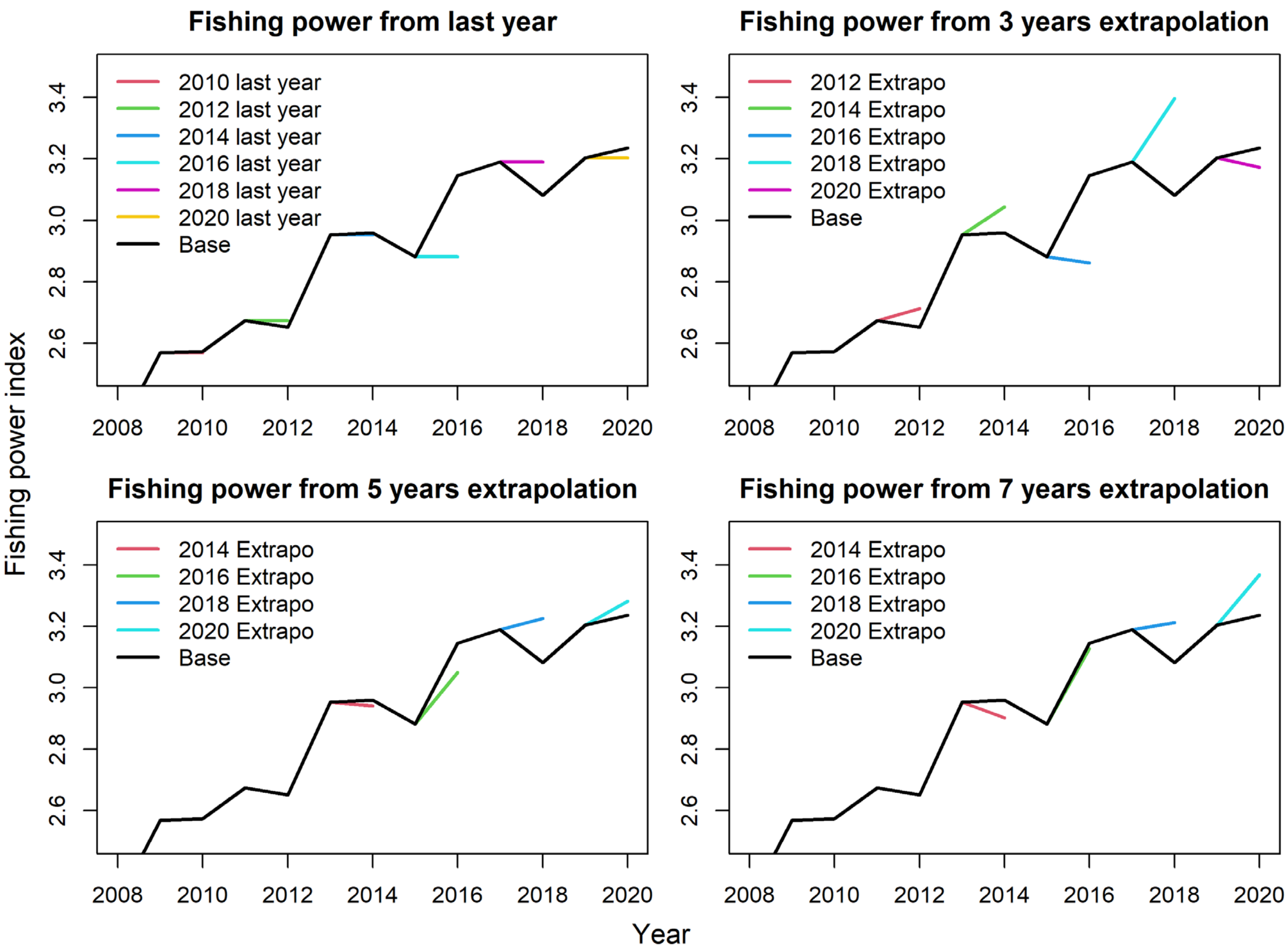
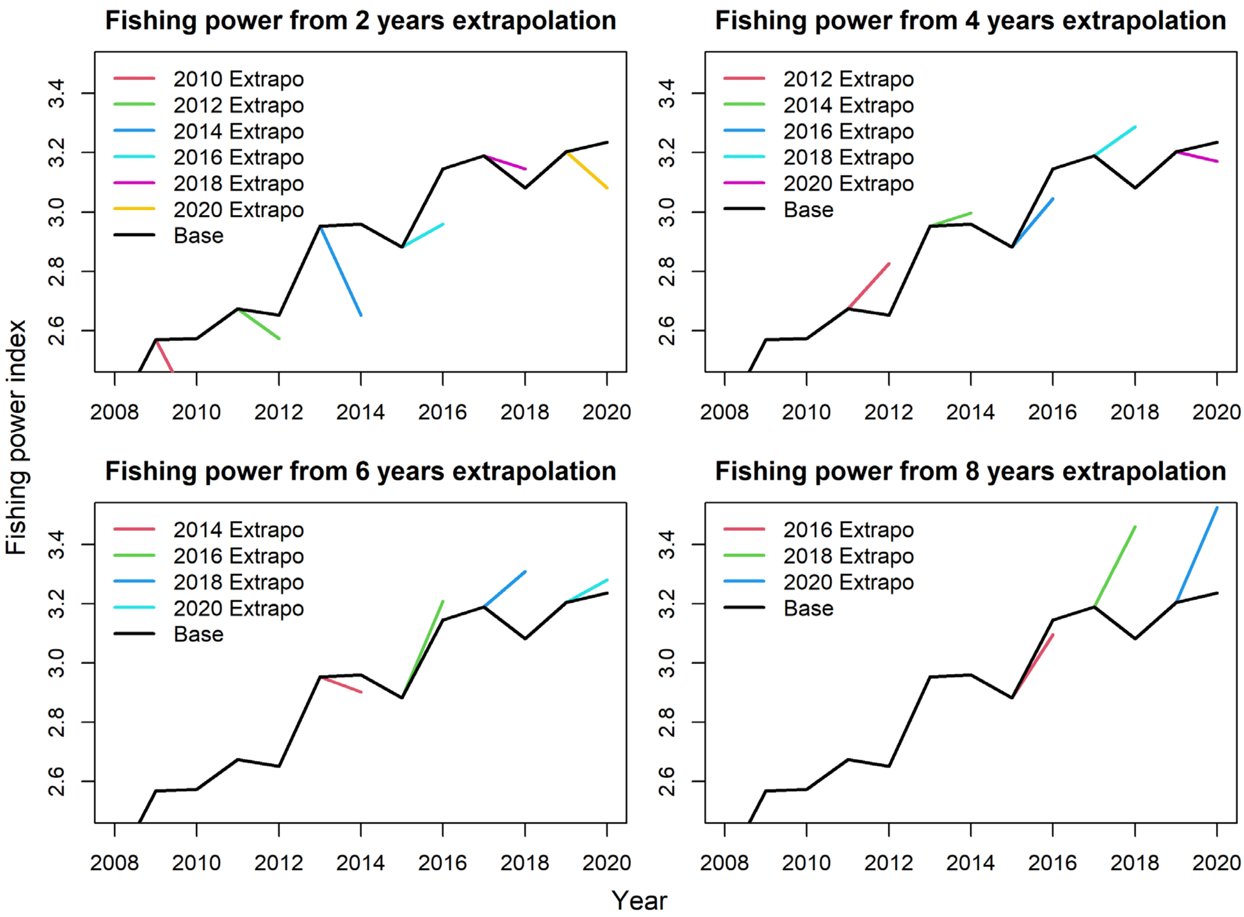


Figure 15. Preliminary simulations to explore the optimal method for estimating fishing power every second year and extrapolating the value in every even year.



5.3 Consider dropping HS rule: 'whether or not the average catch per boat per fishing day in August, September & October is 390 kg'

A recommendation was put forward that this empirical rule be dropped from the revised HS, based on the following:

- The rule was intended to trigger closure of the first (Redleg Banana Prawn) season of the following year. The first season is now permanently closed, rendering this rule redundant. Moreover, the revised HS is more precautionary and hence this additional rule is no longer required.
- Previously, the HS rule specified that Fishing WILL be allowed for the full two seasons in the following year:

  - if data has been provided for less than 100 days of fishing during the full fishing year AND
  - whether or not the HS closure trigger point of 390 kgs per boat per fishing day in August, September & October has been triggered.

The revised HS will use a substantially lower data (effort) cut-off to underpin the definition of data-sufficient versus data-insufficient years for deciding whether or not a stock assessment will be run in any year. Hence for all data-sufficient years, the stock assessment will be used to estimate the stock depletion level relative to the target and limit reference points. Where effort is very low the associated total catch is also expected to be low, and is considered not to result in high mortality attributable solely to fishing (except in the case where the limit reference point has been breached once, as per revised HS).

5.4 Consider whether changes are needed to the Hockey-stick rule applied to the outputs of the current stock assessment.

The application of a Hockey-Stick rule has been problematic because of 1) challenges regarding changing intra-annual fishing patterns, 2) large uncertainty in the assessment due to relying on CPUE data only, and 3) observed differences between the recommended TAE and actual annual effort. Hence it hasn't been possible to define a constant target fishing mortality proportion FTARG as this has varied depending on the pattern of fishing. However, going forward this process will be simpler because the fishing pattern is now expected to be more constant (restricted to second season only).

The stock assessment model has previously not incorporated a default Hockey-stick rule as shown in Figure 16A, but has been applying a modified form as per Figure 16B. For such a highly variable stock, it is more usual to shift the start of the declining limb to lower than the target reference point (B_{MEY}) as the stock is expected to fluctuate below this level 50% of the time on average. The stock assessment therefore uses the B_{MSY} value as the level below which the fishing mortality *F* is reduced relative to a target level (Figure 16B). In addition, the default Hockey-stick rule (Figure 16A) specifies that *F* should be set to zero when the spawning biomass is estimated to be below the LRP in any single year. However, the Redleg HS specifies that if "Redleg Banana Prawn stock size falls below the LRP for the two most recent consecutive years, then the TAE is zero for a year (no fishing in the following year)." Hence the rule needs to take into account that the LRP needs to be breached for two years before the fishery is closed.

Given the highly variable nature of the Redleg Banana Prawn fishery, forward projections of the stock biomass are only meaningful for a year or two. Hence it isn't strictly necessary to use a Hockey-Stick Rule and an alternative would be to recalibrate the target fishing effort each year based on the current stock depletion level. Indeed, MSE testing using the Redleg Banana Prawn MSE developed by Blamey et al. (2020) showed that a more simplified harvest strategy with no Hockey-Stick rule performed similarly and was adequately robust (Figure 17). Nonetheless, ongoing incorporation of a Hockey-Stick Rule is an added feature that usefully highlights the approach to setting the TAE. Moreover, stakeholders at the May 2021 NPRAG meeting agreed that it is a more elegant solution and improves transparency of the overall management approach, whereby larger reductions in fishing effort are recommended whenever the stock is estimated to decrease below the B_{MSY} level. The Hockey-Stick rule operates to rapidly shift the stock back towards the target reference level thereby avoiding approaching the lower biomass limit (B_{LIM}).

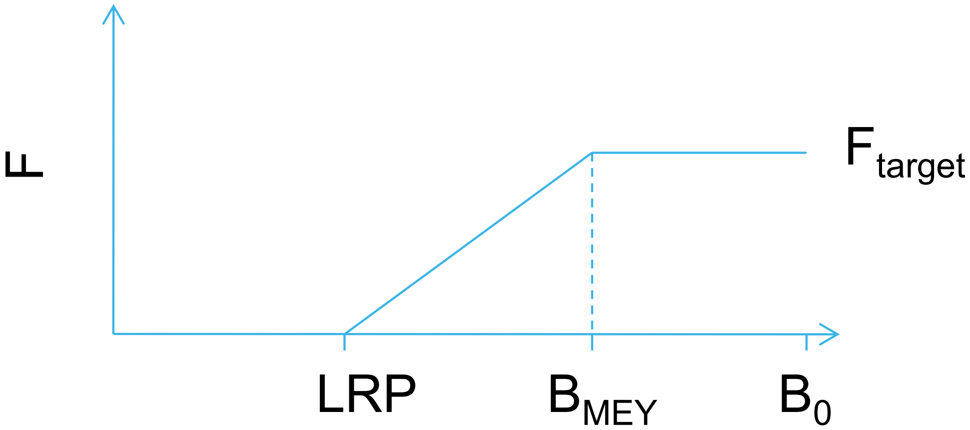
For example, B_{sp} (2020) was estimated at 74% B_{MSY} (Plagányi et al. 2021) so the recommended *F* was 74% of FTARG, which is in turn estimated based on the average level that results in the stock approaching and fluctuating about the target reference level B_{MEY} over the next 2-3 years. Note that the corresponding estimate of the commercially available biomass B_{comm} will also be low and hence it is the multiple of *F* and B_{comm} which is used to calculate the TAE.

The NPRAG reviewed and approved use of a Hockey-Stick formulation as shown in Figure 16B. This included discussion of appropriate recommendations to cover the (unlikely) situation should the stock be estimated to decrease below the LRP in a single year. It was agreed that a pragmatic approach would be to use a fishing effort level equal to half FTARG when calculating the TAE for the following year (noting that the TAE would necessarily be a low number because it would also depend on the stock biomass level which would necessarily be low). If the stock was estimated to again decrease below the LRP in the next stock assessment, then *F* would be set to zero and the fishery closed for the entire next year.

There are a number of reasons why it wasn't considered pragmatic to do a linear extrapolation down to zero to compute *F* when B_{sp} is less than LRP (Figure 16B). Firstly because there is considerable uncertainty associated with the stock assessment given that it relies solely on CPUE and fishing power data. Historically, here also has been reasonably substantial differences between the TAE and the actual observed fishing effort in any year, such that there is insufficient precision to support use of a very precise estimate. In addition, the corresponding number of boat days available to inform estimates of CPUE may be low and hence compromise the reliability of associated CPUE estimates.

Figure 16. Summary of (A) default and (B) revised Hockey-Stick Rule applied to outcomes of the stock assessment. The Redleg Banana Prawn stock assessment uses (B) in that if the stock biomass decreases below the Limit Reference Point (LRP) in the first year, the fishing mortality F proportion is set at half the default value, but if the LRP is assessed to be breached a second time, then F is set to zero for the following year (not shown on plot).

(A)



(B)

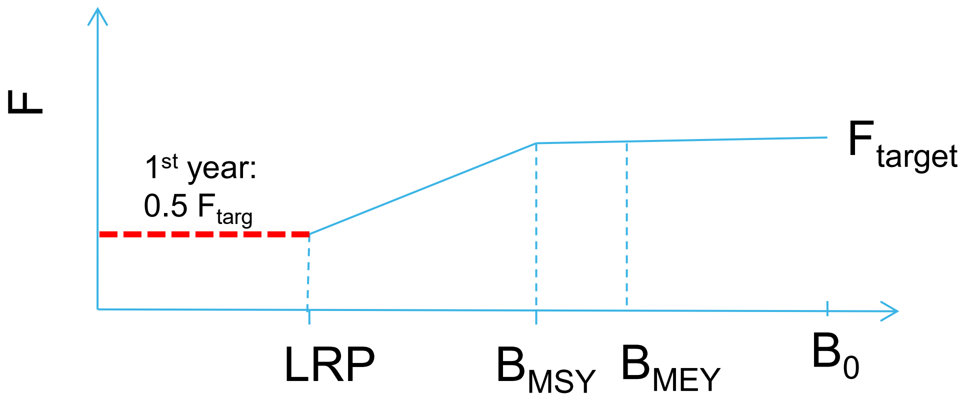
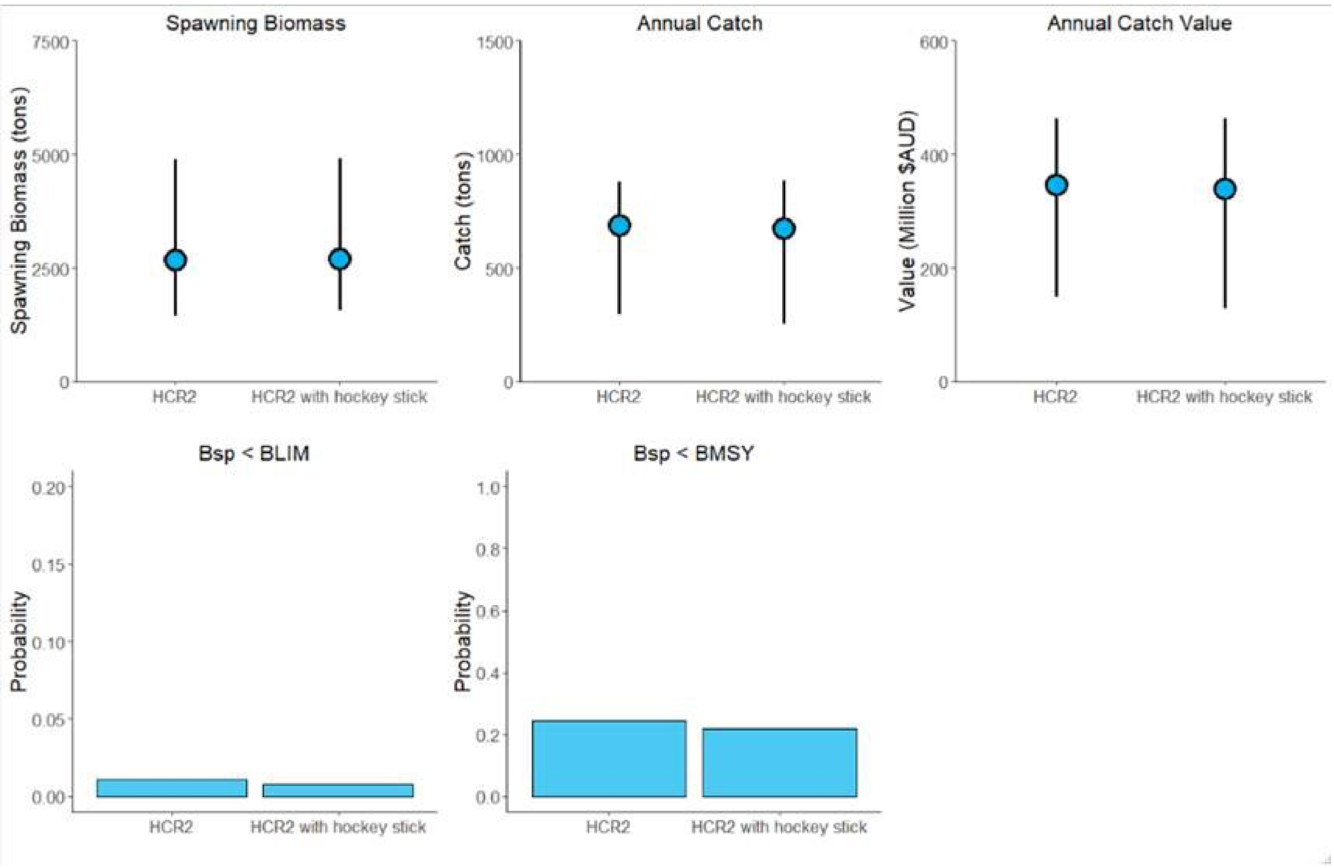


Figure 17. Performance statistics from MSE testing using the Redleg Banana Prawn MSE of Blamey et al. (2020) to compare a simplified implementation of HCR2 with no Hockey-Stick rule included, with an alternative implementation incorporating use of the current Hockey-Stick rule (see Figure 16B).



5.5 Investigate adjustment of reference point values considering that all fishing now occurs in a single fishing season only

Given the large variability in recruitment of Redleg Banana Prawns, it is difficult to precisely estimate resource status as a proportion of the initial (1980) spawning biomass (termed B0) prior to when fishing began (Figure 18). Depending on recruitment that year, B0 could have been up or down and hence a single year's stock biomass estimate is not necessarily a true reflection of the average stock size prior to fishing. Hence, this confounds selection of suitable reference levels relative to B0. In addition, consistent with the management of the rest of the multispecies NPF, the target reference level needs to be expressed in terms of the biomass level (B_{MEY}) at which MEY (Maximum Economic Yield) is achieved. However, 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. The B_{MEY} reference level is therefore computed annually as the average spawning biomass level over the historical reference period. Note that the actual value of reference points are dynamic estimates that need to be updated each year based on the latest stock assessment.

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). The default proxy value for B_{MSY} is 0.4B0. This conforms to the Commonwealth Harvest Strategy under which, in cases where B_{MEY} is unknown, a proxy of 1.2 B_{MSY} (or a level 20% higher than a given proxy for B_{MSY}) is to be used. 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 this project, and in consultation with stakeholders, the appropriateness of these reference levels was reviewed, especially given the major recent change to the fishery related to closing the first season. Available industry representatives and NPRAG members felt that the current proxy B_{MEY} remains a reasonable target level but that this could be re-reviewed in a few years if necessary. Further insights will be 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 for the multispecies nature of the fishery.

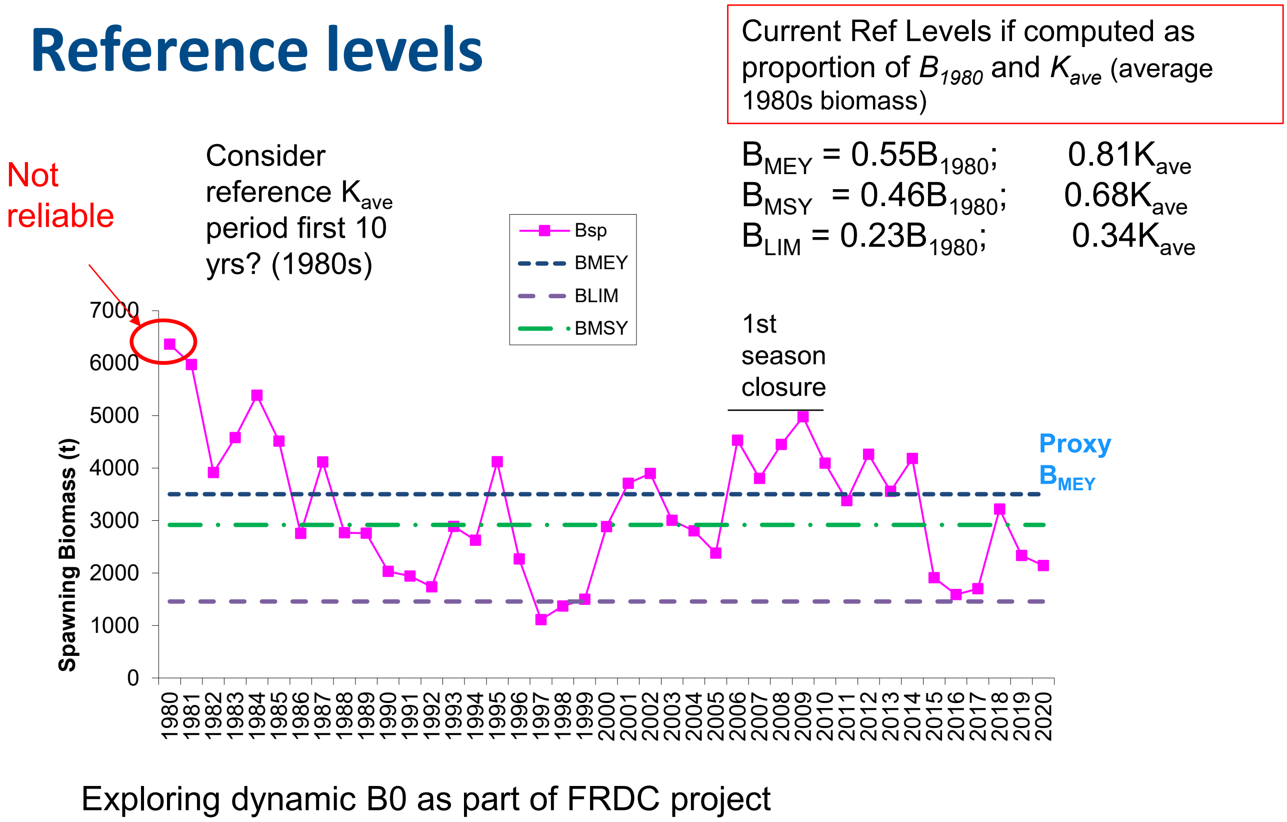
To evaluate how the proxy Redleg Banana Prawn B_{MEY} (i.e., based on average spawning biomass over 1999-2010) corresponds to default B_{MEY} reference levels, we computed the proxy B_{MEY} as a proportion of both the 1980 B0 model-estimated spawning biomass level, as well as a 10-year average B0 spawning biomass level (i.e., average spawning biomass for 1980-1989, termed K_{ave}) (Figure 18). However, discussions at NPRAG suggested the first five years (1980-1984) would provide a better approximation of B0 in 1980, which we term B0(ave). We therefore computed the following relative to the default:

DEFAULT (Smith et al. 2013)		RELATIVE TO B0(1980)		RELATIVE TO B0(average)	
$B_{MEY}/B0_{1980}$	0.48	$B_{MEY}/B0_{1980}$	0.55	B_{MEY}/B0(ave)	0.67
$B_{MSY}/B0_{1980}$	0.40	$B_{MSY}/B0_{1980}$	0.46	B_{MSY}/B0(ave)	0.56
$B_{LIM}/B0_{1980}$	0.20	$B_{LIM}/B0_{1980}$	0.23	B_{LIM}/B0(ave)	0.28

Hence the proxy B_{MEY}, B_{MSY} and B_{LIM} reference levels based on the revised approach, can be considered conservative relative to default specifications. A more conservative reference level is also considered appropriate for Redleg Banana Prawns given that previous sensitivity testing has suggested with some confidence that the steepness *h* of the stock-recruit relationship is estimated to be relatively low (base-case setting is 0.6) (Plaganyi et al. 2021). This is also consistent with estimation of low steepness for Tiger Prawns (Hutton et al. 2018). For highly variable stocks, use of a higher target level also reduces the risk that the stock will occasionally decrease to low levels where recruitment becomes adversely impacted.

Traditionally, fisheries management reference points have been calculated relative to a model estimated starting biomass or a fixed pre-exploitation level for a fishery i.e. B0. However, given stock productivity in some fisheries is either highly variable or likely to change under changing climate, a static B0, which is based on equilibrium conditions for the stock, may not be as meaningful. This is particularly the case under a changing climate or when stock productivity is environmentally driven and undergoes a shift in productivity regime (Vert-pre et al. 2013). Instead, there is increasing recognition that under such scenarios, a non-equilibrium-based dynamic B0 might be more appropriate when assessing indicators of stock abundance (Punt et al. 2014; Berger 2019; Plagányi et al 2019). In other words, instead of setting reference points based on a fixed pre-exploitation starting biomass (a static B0), a dynamic B0 would involve setting reference points based on a projected unfished biomass for a future year. Hence a dynamic B0 implicitly accounts for future anticipated changes in the environment and hence productivity, and it evaluates what the impact of fishing will be on the stock over the coming period. Given the variability in Redleg Banana Prawn productivity, as well as the expectation of an increasingly variable environment, there might be a need to incorporate a dynamic B0 in the calculation of reference points in the future. There is currently an FRDC-funded project looking at the potential use of a dynamic B0 vs. the traditional static B0 across several Australian fisheries, of which Redleg Banana Prawns are one of the case studies.

Figure 18. Total annual spawning biomass (t) trajectory using the 2021 Base Case model of Plagányi et al. (2021) compared with the target spawning biomass level (B_{MEY}), the biomass level (B_{MSY}) corresponding to Maximum Sustainable Yield (MSY) and limit reference level (B_{LIM}).



5.6 Redleg Banana Prawn CPUE trigger considerations

<u>MSE Testing</u>

An in-season trigger is implemented for White (Common) banana prawns *P. merguiensis* (first season only), and hence this type of rule is already well-understood by fishers and managers who are used to providing in-season data and calculating an average CPUE for vessels in the fishery. The Redleg Banana Prawn MSE testing therefore included consideration of a rule (termed HCR4) that entailed use of a monthly CPUE trigger to close the fishery (Figure 19) (Blamey et al. 2020, 2021). HCR4 specified that if the monthly CPUE drops below 500 kg/day, the fishery closes for the rest of the season (either season 1 or season 2) and will re-open the following season (Figure 20). This rule performed well but was not the final rule preferred by stakeholders largely because of a number of associated logistical issues and costs, as outlined in (Blamey et al. 2020, 2021). Two important considerations that would need to be included in the CPUE calculation so that a reasonably representative average CPUE could be calculated were: 1) that average CPUE needs to be computed to account for the fact that fishing occurs over neap tides, and 2) that a lower limit be set for how many boat days are required (e.g., minimum 5-10 boat days). The CPUE would need to be the nominal CPUE and hence would likely need to be reviewed every few years and account for fishing power effects, as well as other factors that confound our interpretation of CPUE as a relative index of abundance.

MSE testing showed this rule would considerably improve the performance of the fishery in terms of key performance statistics such as risk to the stock (biomass falling below B_{LIM}) and risk of fishery closure (Figure 19) (Blamey et al. 2020, 2021). But similar improvements to performance are now anticipated based on the recent implementation of HCR2 which involved closing the first fishing season. It is therefore not necessary to formally implement HCR4. Nonetheless voluntary consideration by industry of a trigger approach would enable rapid adaptive management to limit effort whenever there are indications that the stock biomass is reduced or CPUE is less favourable.

As evident from MSE testing results, use of a trigger results in substantial reduction in the probability of extremely low CPUEs (the lower range of the confidence interval) for Aug-Oct relative to other approaches (Figure 20). This has the advantage of further safeguarding the stock in the event that there is substantial effort directed on the fishery in a year when stock biomass is low or the stock is fairly heavily depleted towards the end of the fishing season. Moreover, in the absence of more refined computations to guide the fishery towards achieving MEY, a trigger provides guidance to the fishery to roughly account for economic considerations. This may be particularly important given the relatively high costs of fishing in the JBG which we comment on below. However, not all costs are greater in the port from which the JBG is accessed; for example fuel is cheaper in Darwin than the price paid on the barge in the Gulf of Carpentaria.

Economic considerations

To maximise profits in a fishery, fishers should ideally operate up to the point where the marginal revenue (i.e., the revenue per day) is equal to the marginal cost (the cost per day of fishing) (Pascoe et al. 2020). However, Pascoe et al. (2020) showed that for the Redleg Banana Prawn fishery, changes in effort levels may be driven by conditions in alternative areas, namely the opportunity cost may drive changes in effort as fishers shift effort from one part of the fishery to another with more favourable catch rates and prices.

Here we explore further what average nominal CPUE level might usefully inform a voluntary reference level for fishers when fishing performance may be deteriorating towards the end of the fishing season. Given that CPUE is worked out over neap tides (restricted periods each month) and that there are no specific detailed cost data for the Redleg Banana Prawn fishery; it may not be a good idea to pursue a MEY economic trigger. Price data for Redleg Banana prawns are available (Figure 21); although a trigger relies on a predicted price for the season. Further, for an economic trigger fishery-specific estimates for capital cost and gear cost per unit of effort are required, and marketing costs. Cost estimates for variable costs could be obtained by mining the existing extensive cost data obtained for the Tiger Prawn and Common Banana Prawn metiers each year and making reasonable assumptions. That is, interpolate to account for 24-hour fishing (that occurs on 7-8 day fishing bi-monthly trips) with long steam distances to determine fuel use per day; and account for lower fuel costs out of Darwin port (20% less than fuel off barge in Gulf of Carpentaria). An alternative suggestion would be to formulate a bio-economic model that would estimate MEY (Sean Pascoe pers comm.); although this approach will be subject to the same data limitations that exist for the calculation of a trigger.

Figure 19. Key performance metrics across the five harvest control rules, for the reference set of Operating Models (i.e. averaged across all six OMs). Box and whisker plots (upper two panels) show the median (central bold line), the 75th and 25th percentiles (the blue box) and the range of projected values, excluding outliers (the whiskers). (extract from Blamey et al. 2020).

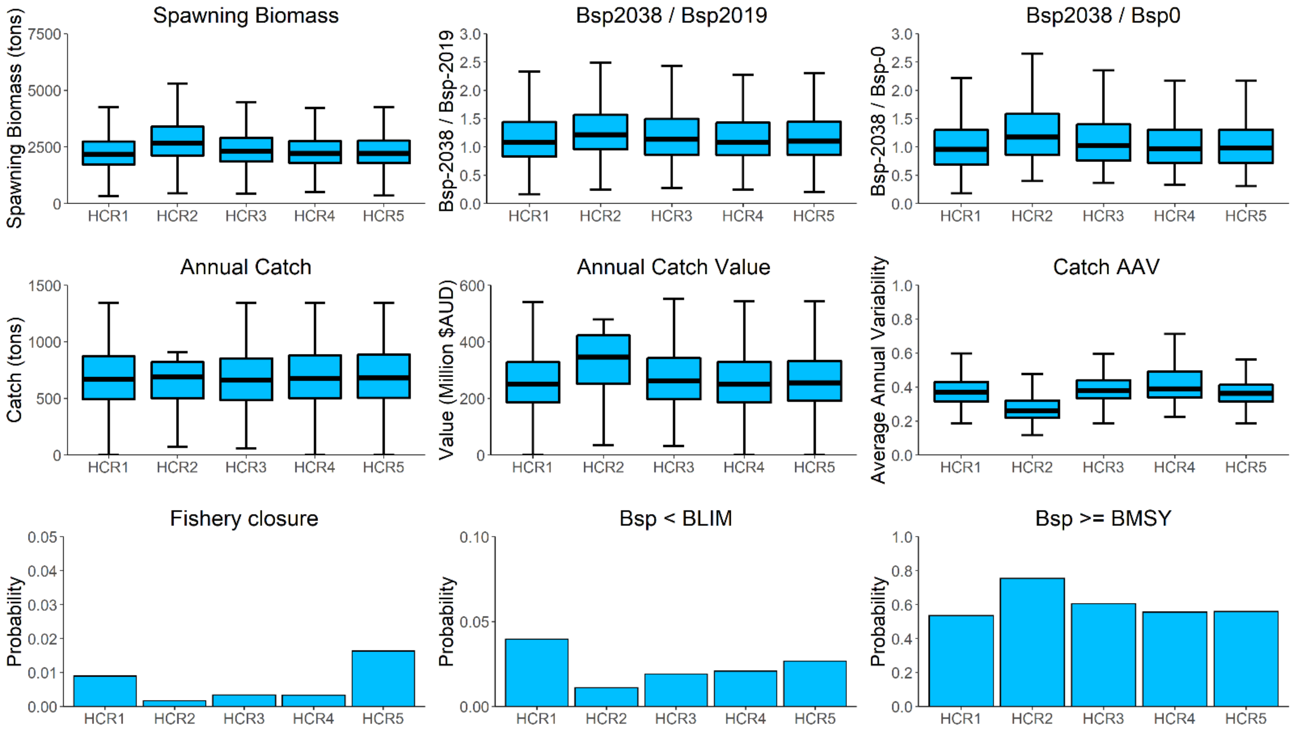


Figure 20. Catch-per-unit-effort (CPUE) across the five harvest control rules, for the reference set of Operating Models (i.e., averaged across all six OMs). Box and whisker plots show the median (central bold line), the 75th and 25th percentiles (the blue box) and the range of projected values, excluding outliers (the whiskers). The red horizontal line indicates the mean catch rate (390kg boat^{-1} day^{-1}) that is currently used as a trigger (as part of the current harvest strategy) to close the first fishing season of the following year, if catch rates fall below this level during Aug-Oct. (extract from Blamey et al. 2020).

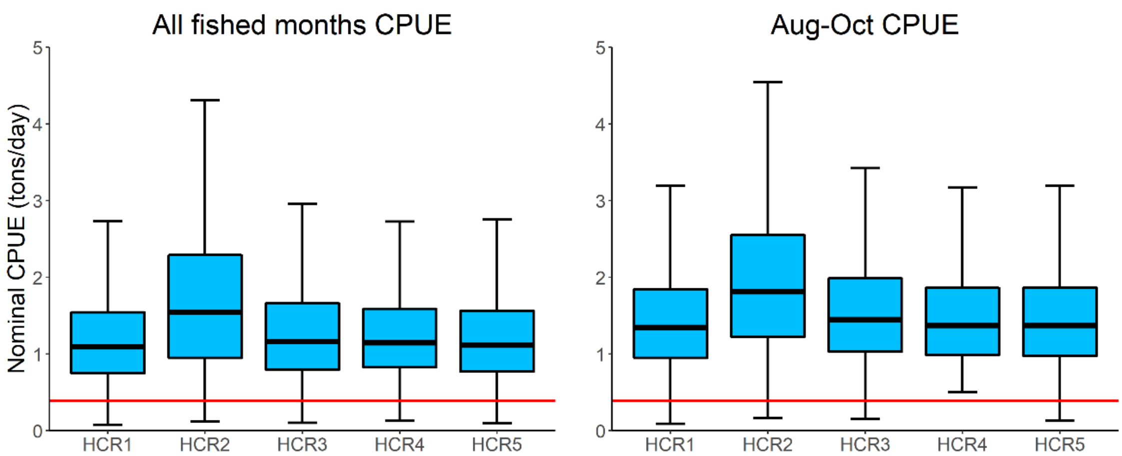
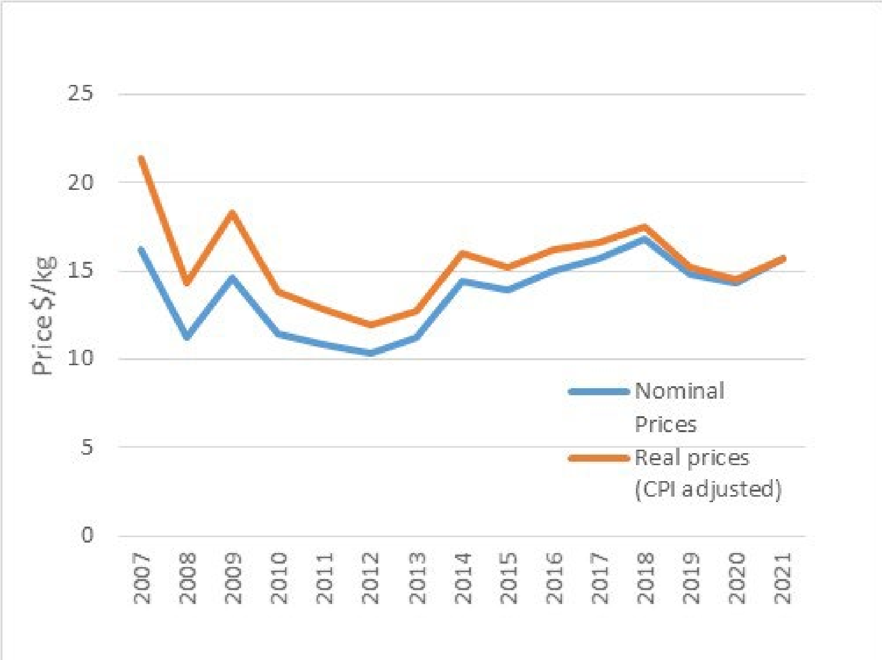


Figure 21. Redleg banana prawn specific price data (average over all grades). Nominal and Consumer Price Index (CPI) adjusted (CPI index sourced from ABARES; Price data provided by one company).



Voluntary trigger approach for rapid adaptive management to limit effort

Given indications that the stock biomass is reduced or when CPUE is economically unfavourable, catch triggers that limit effort are useful tools in some fisheries. We used recent CPUE for the period 2010 to 2020, to further assess whether a monthly average CPUE of 500 kg/day would be a useful voluntary trigger to guide fishers to limit effort. We compared monthly nominal CPUE trends over the years 2010 to 2020, and separated these into good and bad years. We defined 'good' years as those for which the Redleg stock assessment model estimated the stock to be 80% or more of the B_{MEY} level and conversely for 'poor' years (Table 7).

When considering 'good' years, the nominal CPUE was almost always well above 500 kg/day (Figure 22A). The exceptions were June 2013 which has low associated effort and October-November 2011. Note that the June 2013 average may be an artefact of a neap tide stretching across two months – future analyses may disaggregate the data and realign with neap tide cycles. Hence if fishers in these years stopped fishing the month after the average fell below 500 kg/day, they would have ceased fishing only in November 2011 when both catch and CPUE were extremely low. Note that at the end of 2014, the year preceding the El Nino period of 2015-16, the November CPUE remained reasonably high at 630 kg/day (Figure 22A).

When considering ‘poor’ years, the nominal CPUE was often below 500 kg/day (Figure 22B). This was the case almost throughout 2015-16, apart from a slightly higher value of 580 kg/day in August 2016 (with low corresponding effort). In 2017, the CPUE was initially high in the second season, but then fell below 500 kg/day in September through to November. If the trigger had been used to cease fishing in October, this would have resulted in 22t less than what was caught, being caught. The 22t was 6% of a total catch of 374t that year, which was the largest catch the hypothetical trigger would have resulted in being lost over the years 2010-2020. Hence a guidance trigger of 500 kg/day is not considered overly conservative.

On the other hand, if one considers a higher trigger value such as 600 kg/day, this may be too conservative considering, for example, that it may have caused fishing to cease in September 2018 (Figure 22A) when 16% of the annual catch was taken.

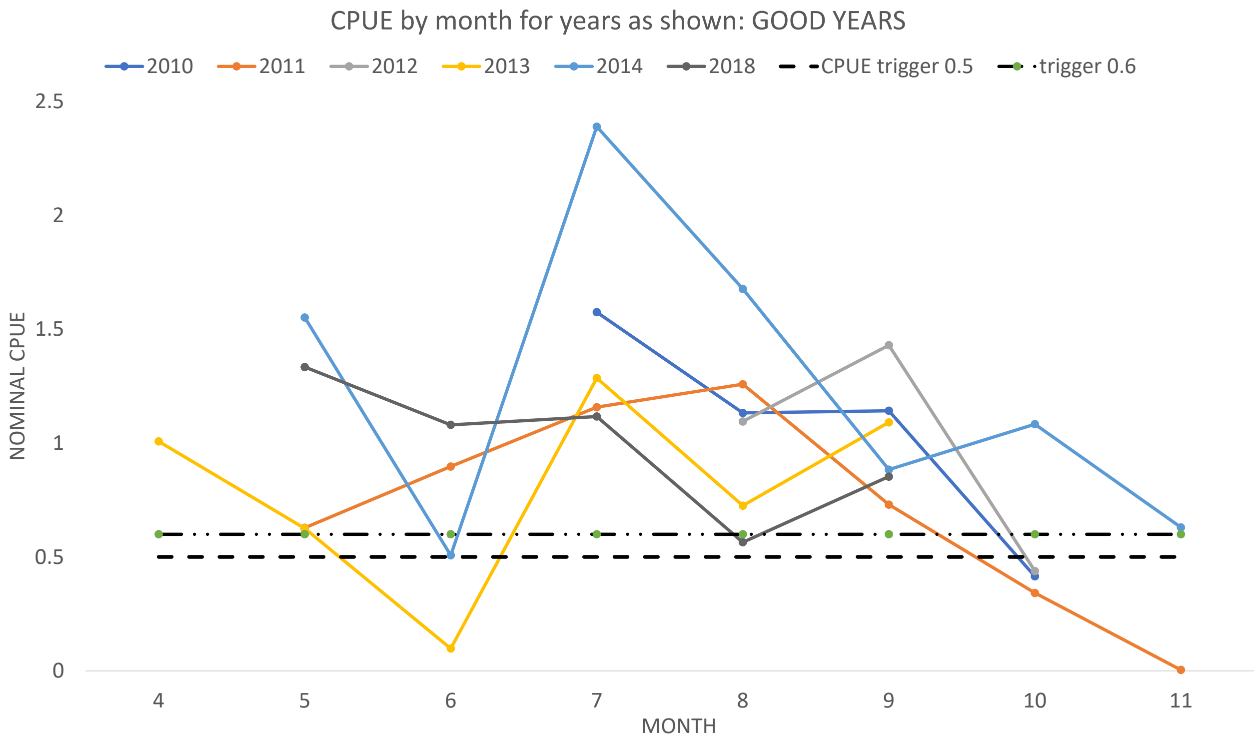
Further justification for suggesting that a monthly average CPUE trigger of 500 kg/day may be a useful guide to trigger fishers ceasing fishing towards the end of the season is because it is a relatively low 39% of the median nominal CPUE over the period 2010-2020. In addition, the target spawning biomass level that is considered a proxy for B_{MEY} is computed over the reference period 1999 to 2010. Over this period, the average annual nominal CPUE was 745 kg/day and hence it follows that 500 kg/day is approximately two-thirds (67%) of the CPUE that corresponds on average to the target level. The value of 500 kg/day suggests that the stock is roughly halfway between B_{LIM} and B_{MEY} and hence that fishing may no longer be optimal and if that CPUE level is met that the stock is depleted below the B_{MEY} and B_{MSY} levels.

Table 7. Summary of recent annual CPUE and stock assessment estimates of stock status shown as B_{sp}/B_{MEY} and B_{sp}/B_{LIM}, with 'poor' years – defined as years where spawning biomass B_{sp} is less than $0.8xB_{MEY}$ – shaded in pink.

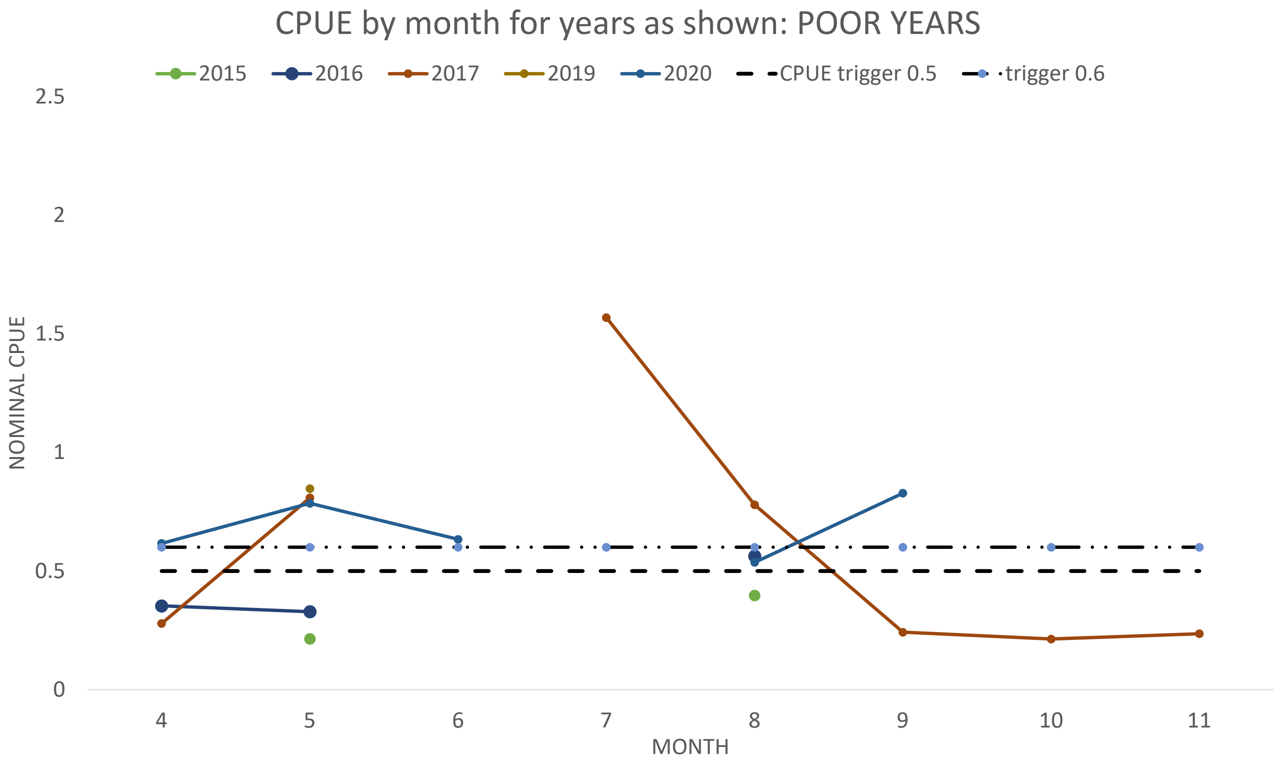
	CPUE_annual_STD	Bsp/B_{MEY}	Bsp/B_{LIM}	Catch_annual (t)
2010	0.163	1.17	2.80	233.2
2011	0.271	0.96	2.31	435.3
2012	0.283	1.21	2.92	178.9
2013	0.179	1.01	2.43	374.4
2014	0.330	1.19	2.86	819.6
2015	0.032	0.55	1.31	29.5
2016	0.075	0.45	1.09	33.1
2017		0.48	1.16	364.5
2018	0.140	0.92	2.20	237.6
2019	0.186	0.67	1.60	47.3
2020	0.053	0.62	1.48	133.4

Figure 22. Plots of the nominal monthly average CPUE (t/boat day) for (A) 'good' and (B) 'poor' years (see Table 7) for all years since 2010, shown relative to a hypothetical trigger value of 0.5 t/boat day (=500 kg/boat day).

(A)



(B)



5.7 Consideration of other data

Size grade data

The older, larger Redleg Banana Prawns, which are graded “U10” and fetch a higher price, have ranged from contributing approximately 4% to the total annual catch and up to around 40% of the catch between 2004 and 2020. Years with largest U10 catch include 2005, 2009, 2010 and 2014 (Figure 23). Across the whole period (2004-2020), the proportion of these U10 prawns increased throughout the year, while the proportion of smaller prawns declined (Figure 24). Redleg Banana Prawns grow through the year and are largest towards the end of the year, where they spawn in the fourth quarter (Loneragan et al. 1997, 2002). Some of those large prawns will survive into the following year, which is likely why a small proportion of U10s may have been caught in the first season during April-May (Figure 24-Figure 25). However, in general, the size grade data show that the larger prawns are usually caught in the second season and indeed in almost all years, the proportion of larger prawns caught was greatest over August-December, increasing through the season (Figure 25).

When considering the average catch of U10 prawns in years when only the second season was open to fishing (2007-2010) compared to subsequent years when both seasons were open (2011-2020), the average catch was almost double for the second-season only fishing-years (i.e. 2007-2010) (Table 8). This supports the rationale behind the recently adopted change to the HCR (Blamey et al. 2020), that by closing the first fishing season, not only would one reduce risk to the stock in anomalous environmental years, but the average catch would be expected to be larger and more valuable when fishing only the second season. The smaller prawns would not be caught early in the year and instead would have time to grow by August.

We found a significant positive correlation between August grade U10 catch and the total second season catch ($r = 0.45$, $p = 0.003$; Figure 26). Thus, the quantity of U10 prawns caught in August could be a possible indicator for whether the fishing season (season 2) is likely to be a good vs poor season.

It is difficult to identify any trends that point towards a temporal change in the proportion of large prawns caught over time, thereby suggesting that the timing of recruitment or maturity of Redleg Banana Prawns may (or may not) be changing under more variable extreme environmental years. However, trends may emerge as more data become available in years ahead, or through exploration of historical unpublished data (see next section).

Figure 23. Proportion of size grades making up the total catch each year for the period 2004-2020.

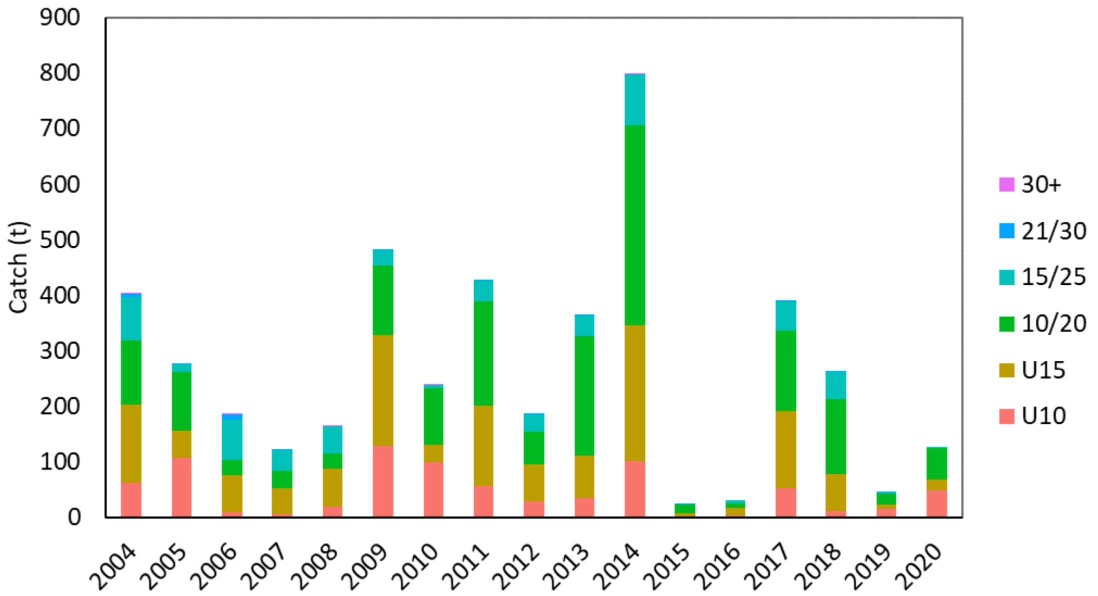


Figure 24. Proportion of size grades making up the total catch shown per month for the period 2004-2020.

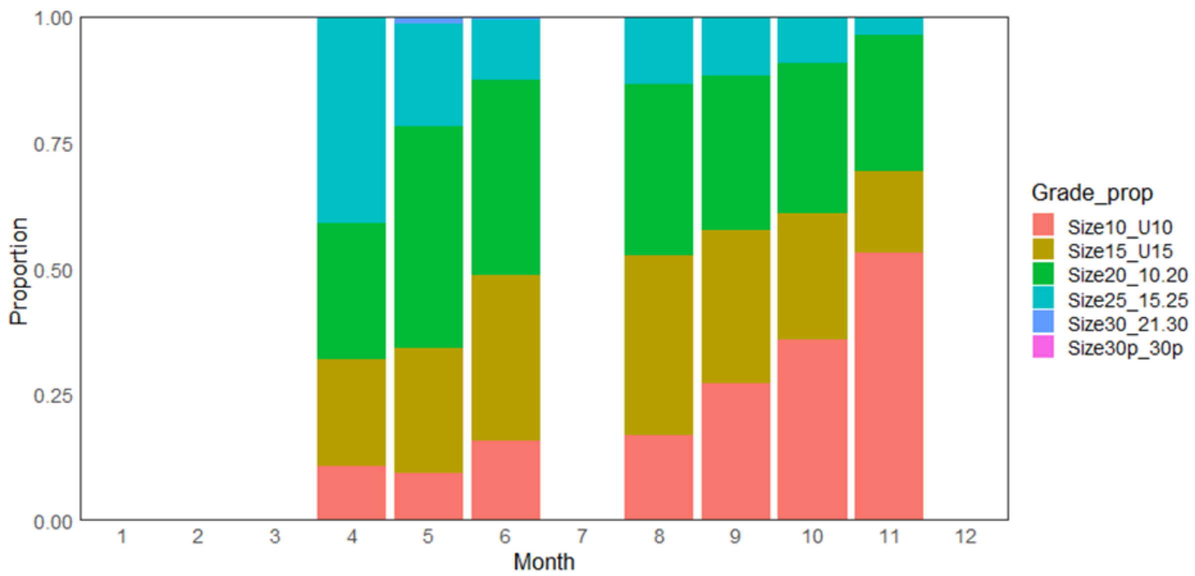


Figure 25. Proportion of size grades making up the total catch shown per month for each year from 2004-2020. Note the years 2015, 2016 and 2019 had very small catches.

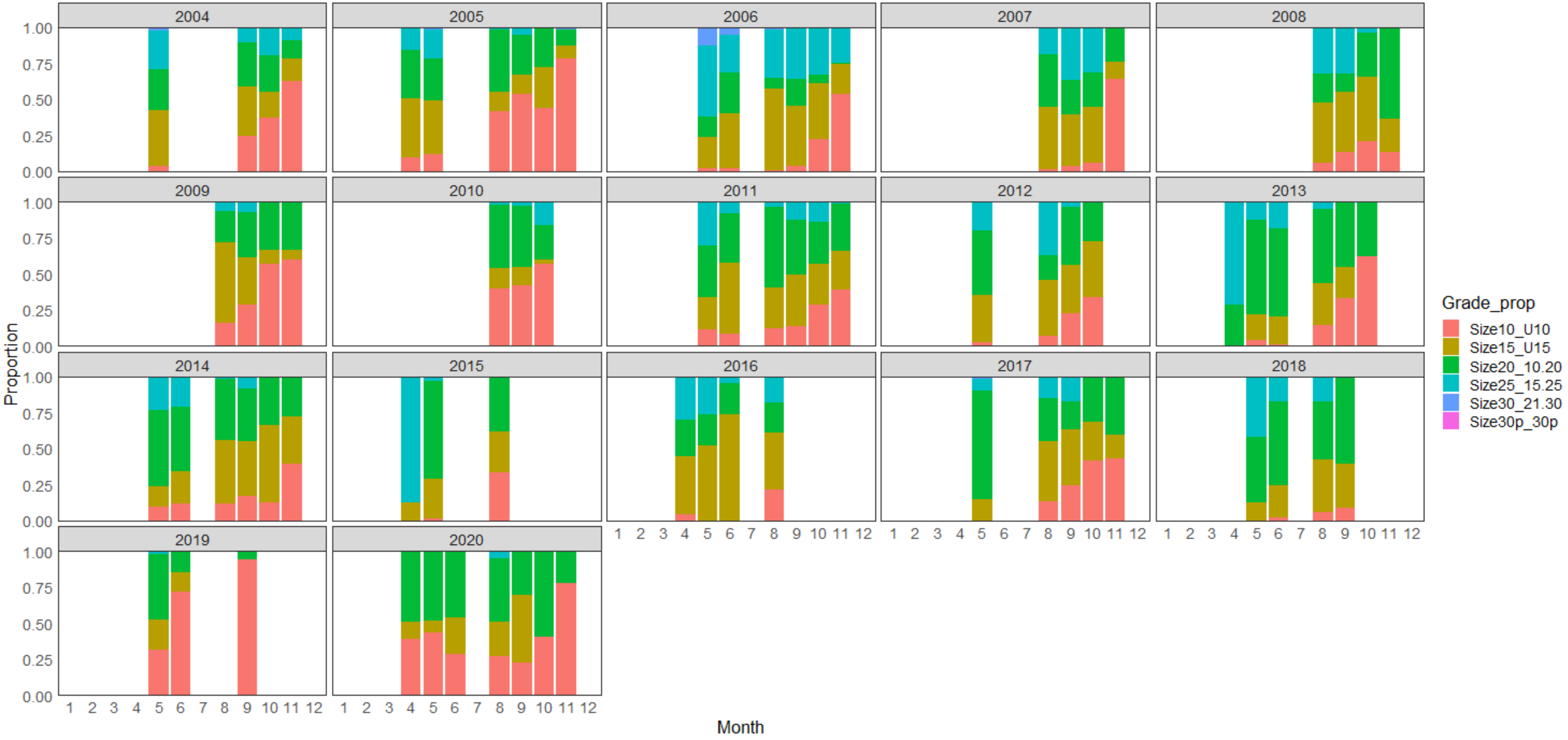
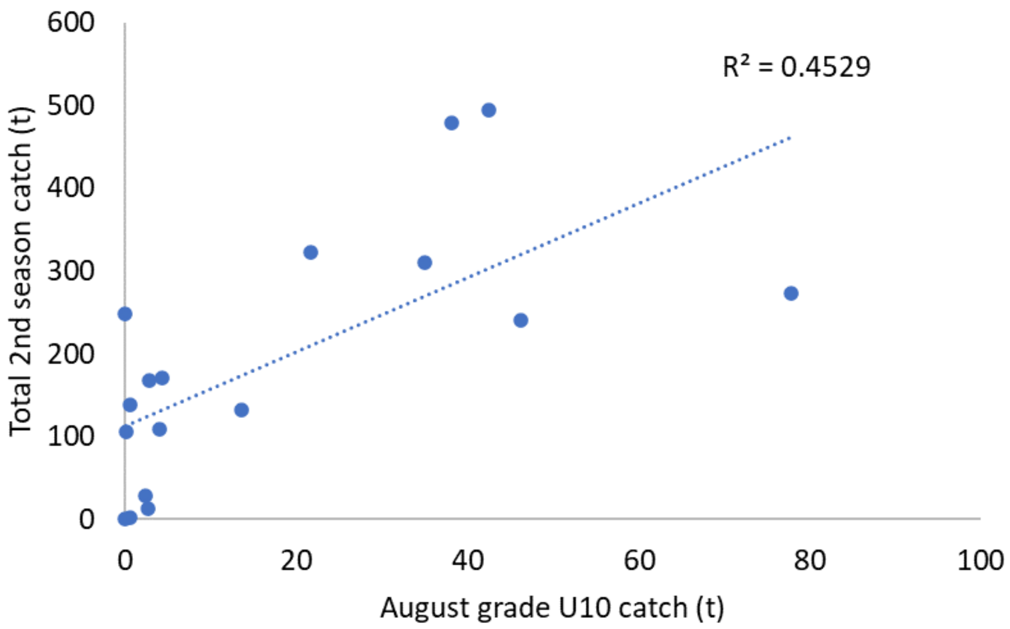


Table 8. Average weight (t) and average proportion of catch per year of Grade U10 Redleg Banana Prawns caught in the JBG when the fishery is open both seasons vs only the second season

	U10 average weight (t)	U10 average proportion of catch
First & second season open (2011-2020)	35	0.16
Second season only open (2007-2010)	63	0.21

Figure 26. Correlation between Redleg Banana Prawn Size U10 catch (t) in August and total second season Redleg Banana Prawn catch (t)



NTDPI data

The NTDPI carried out early exploratory prawn cruises in the GoC, top end and the JBG. Some of these data have been captured through a CSIRO-funded data recovery project. Data on Redleg Banana Prawns from the JBG were collected from surveys carried out from 1988/89 – 1991. The objective of these surveys was to collect information on Redleg Banana Prawns in JBG and combine it with relevant information in the literature with respect to other

P. indicus fisheries in Asia, to help inform management. As such, data were collected to investigate the relationship of size composition and depth, size at recruitment, reproductive biology, and size distribution in inshore areas (as possible indicator of recruitment sources). Datasheets included cruise reports, deck logs, and animal measurements, as well as draft versions of a report. Most of the JBG data have now been captured electronically. These data may be useful in helping determine whether there have been shifts in growth, recruitment or size over the last 30 years. They are being collated for incorporation in future analyses.

Environmental drivers and revisions to the Harvest Strategy

Previous work (Plagányi et al. 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 (as a proxy for sea level) 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 (Blamey et al. 2021).

As we collect more data over the next few years, our understanding of environmental drivers (Plagányi et al. 2020) 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. However, in the absence of a fishery-independent survey it will be very difficult to attribute the effects of multiple factors on the fishery.

We therefore recommend that the two key environmental indicators recommended, namely the January Southern Oscillation Index (as a proxy for sea level) and the combined January to February cumulative rainfall, continue to be collected and assessed on an annual basis. We also recommend ongoing collection and analysis of available price data for Redleg Banana prawns to assist in improving understanding of economic drivers. This may be particularly important given recent COVID-19 related market and other shocks to global trade systems. Whereas we have focused on the stock assessment in this project, we draw attention to the growing calls for fishery businesses to pay more attention to supply chain risks and business continuity planning (Ogier et al. 2021, Plagányi et al. 2021). Both qualitative and quantitative approaches (e.g. Plagányi et al. 2014) can be used in combination with market demand (Hobday, Bustamante et al. 2014, Pascoe, Schrobback et al. 2021) to analyse the resilience of supply chains. In some cases, transformative changes may be needed to develop more resilient supply chains to ensure the ongoing sustainability and security of seafood and other natural resources production (Lim-Camacho, Plagányi et al. 2017).

6 Benefits and Adoption

The Redleg Banana Prawn stock assessment provides estimates of stock status and in accordance with the NPF Harvest Strategy, the predictive component of the model supports recommendations for the Total Allowable Effort (TAE) for this sub-fishery of the Northern Prawn Fishery. Improvements to the stock assessment contribute towards maintaining and demonstrating the sustainability of the NPF target species. This project has also progressed in parallel with changes being made to the Redleg Banana Prawn harvest strategy, both to inform these changes and in turn to ensure that the revised stock assessment is closely aligned with the revised Harvest Strategy.

As the primary clients of this work are the management group of the fishery, that is AFMA, NORMAC, NPRAG and NPF Industry Pty Ltd – 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 several of the recommendations have been endorsed by the NPRAG and NORMAC.

Specific achievements adopted or supported were:

The stock assessment model was modified to ensure it aligns with changes made to the harvest strategy.

The revised HS will use a substantially lower data (effort) cut-off of 70 boat days to underpin the definition of data-sufficient versus data-insufficient years for deciding whether or not a stock assessment will be run in any year, as well as the fishing power model.

Stakeholders at the May 2021 NPRAG meeting agreed that incorporating a ‘Hockey-Stick Rule’ in the Harvest Strategy improves transparency of the overall management approach, and adopted minor changes to the rule. The Hockey-Stick rule operates to rapidly shift the stock back towards the target reference level avoiding the lower biomass limit. Following review, the target and limit reference levels remained as before, based on use of a proxy

B_{MEY} calculated as 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.

8 Further Development & Planned Outcomes

This report has been discussed and agreed at a number of NPRAG meetings to inform revisions to the harvest strategy. We acknowledge that it is difficult to accurately predict all changes that may result in response to the changes to the harvest strategy and hence the NPFRAG discussed that it will be necessary and advisable to review in 3-5 years' time some of the recommended settings proposed as part of this study. In particular, the data-sufficient threshold number should be reviewed in 3 years (2025) to enable the consideration of the impacts of the first-season closure on the data availability, pattern of fishing and assessment. New data will be available by 2025.

Should industry want to consider a voluntary trigger approach, more detailed economic analyses could be undertaken to review the suggestion that a monthly average CPUE of 500 kg/day would be a useful voluntary trigger to guide fishers to limit effort whenever there are indications that the stock biomass is reduced or CPUE is less favourable.

Future work could validate the usefulness of additional indicators such as the quantity of U10 prawns caught in August as a predictor of whether the fishing season (season 2) is likely to be a good vs poor season.

As more data become available over time, it may be possible to further refine the stock assessment and HS to better account for environmental variability such as due to El Niños.

A related FRDC study is exploring use of a dynamic B0 as a reference level and use of a dynamic reference level could be considered in future.

As with most other fisheries, there is an ongoing need to evaluate potential future impacts on the stock of other cumulative anthropogenic pressures such as climate change and water resource development planning.

9 Conclusion and Recommendations

Based on the outcomes of the Redleg MSE project (Blamey et al. 2020, 2021), the harvest strategy and stock assessment model have been modified accordingly to ensure they align with operational changes made to the harvest strategy. Below follows a short summary of some key conclusions and recommendations:

- The Redleg Banana Prawn assessment model has been revised, with further changes to be incorporated in the 2022 stock assessment model. The changes will focus on meeting the requirement for the current harvest strategy, including refinement of outputs for recommended TAE;
- The revised HS will use a substantially lower data (effort) cut-off to underpin the definition of data-sufficient versus data-insufficient years for deciding whether or not a stock assessment will be run in any year. Hence for all data-sufficient years, the stock assessment will be used to estimate the stock depletion level relative to the target and limit reference points. Where effort is very low the associated total catch is also expected to be low based on the catch history.
- It was recommended that the CPUE empirical rule previously incorporated in the Harvest Strategy be dropped from the revised HS, because the rule was intended to trigger closure of the first (Redleg Banana Prawn) season of the following year. The first season is now permanently closed, rendering this rule redundant. Moreover, the revised HS is more precautionary and hence this additional rule is no longer required.
- The reference point values used for Redleg Banana Prawns have been reviewed and available industry representatives and NPRAG members felt that the current proxy B_{MEY} remains a reasonable target level but that this could be re-reviewed in a few years if necessary. Further insights will be 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 for the multispecies nature of the fishery.
- Stakeholders at the May 2021 NPRAG meeting agreed that incorporating a Hockey-Stick Rule in the Harvest Strategy is a more elegant solution than alternatives and that it improves transparency of the overall management approach. Larger reductions in fishing effort are recommended whenever the stock is estimated to decrease below

the B_{MSY} level. The Hockey-Stick rule operates to rapidly shift the stock back towards the target reference level thereby avoiding approaching the lower biomass limit (B_{LIM}). One recommended revision covers the (unlikely) situation should the stock be estimated to decrease below the LRP in a single year. It was agreed that a pragmatic approach would be to use a fishing effort level equal to half FTARG when calculating the TAE for the following year (noting that the TAE would necessarily be a low number because it would also depend on the stock biomass level which would necessarily be low). If the stock was estimated to again decrease below the LRP in the next stock assessment, then *F* would be set to zero and the fishery closed for the entire next year.

- Should industry want to consider a voluntary trigger approach, our analyses suggest a monthly average CPUE of 500 kg/day would be a useful voluntary trigger to guide fishers to limit effort whenever there are indications that the stock biomass is reduced or CPUE is less favourable.
- We considered ways of incorporating more information in the assessments, for example, size information from commercial prawn grade data. Analysis of the size grade data showed that the larger prawns are usually caught in the second season and indeed in almost all years, the proportion of larger prawns caught was greatest over August-December, increasing through the season. This supports the rationale behind the recently adopted change to the HCR (Blamey et al. 2020), that by closing the first fishing season, not only would one reduce risk to the stock in anomalous environmental years, but the average catch would be expected to be larger and more valuable when fishing only the second season. Redleg Banana Prawns would not be caught early in the year (i.e. before August) and instead would have time to grow.
- We recommend that the two key environmental indicators, namely the January Southern Oscillation Index (as a proxy for sea level) and the combined January to February cumulative rainfall, continue to be collected and assessed on an annual basis.
- We recommend ongoing collection and analysis of available price data for Redleg Banana Prawns to assist in improving understanding of economic drivers and returns, and opportunity cost of fishing for other prawn species in other NPF regions.

- We found a significant positive correlation between August grade U10 catch and the total second season catch. As further data become available, this relationship may be strengthened. Hence, we propose that the quantity of U10 prawns caught in August could be a possible indicator for whether the fishing season (season 2) is likely to be a good vs poor season. This may be particularly useful as an indicator in low effort or non-assessment years as available grade data could be used to rapidly to assess the August grade U10 catch proportion.
- Retrospective model simulations were run to inform final choice of a minimum number *nmin* of boat days that can be used to define a data-sufficient year. From a stock assessment perspective, we assumed a reasonable acceptable error in assessment of the stock status is 10%. These analyses suggested that the final choice of *nmin* is likely to be in the range 60-80 boat days, and towards the upper end of the range, noting also there is a precedent for 75 days in 2019. The February 2022 NPRAG agreed that the suitable minimum threshold to run a Redleg Banana Prawn assessment be set at 70 total fishing days.
- Under ‘low data’ conditions, the main concern from a fishing power perspective is related to bias. The fishing power model previously performed satisfactorily (e.g., based on checking for systematic changes in residuals) when using 72 boat days and hence the data sufficient cut-off number of 70 days is also recommended as the lower data limit for the fishing power analysis.
- The data-sufficient threshold number should be reviewed in 3 years (2025) to enable the consideration of the impacts of the first-season closure on the data availability and assessment (when updated data will be available). If there are substantial changes in the fishing pattern and they are unprecedented this might present a flag to review, as our study focused on past fishing patterns.

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Appendices

Appendix 1. Stock Assessment 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 19780-1988, another vector to the period 1989-2006 (i.e. post end of year NPF closure), to 2007-2010 (first season closure) period and recent period 2011-2019 (and reverting to the 2007-2010 vector with effect from 2020); 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:

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

with

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

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 Beverton-Holt stock-recruitment relationship (Beverton and Holt, 1957), allowing for annual fluctuation about the deterministic relationship for Quarters 1 and 2:

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

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

where

α, β are spawning biomass-recruitment relationship parameters,

$\varsigma_{y,s}$ reflects fluctuation about the expected recruitment for year *y* and quarter *s*, which is assumed to be normally distributed with standard deviation σ_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 R_0, and hence the stock recruit parameters.

Likelihood function

The model is fitted to all available standardised 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 (calculated) 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:

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

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

The catchability coefficient q is also estimated using maximum likelihood:

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

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:

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

where

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

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 due to recent changes in the Harvest Strategy, projections will now assume zero fishing effort in the first two quarters of each year. 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:

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

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

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

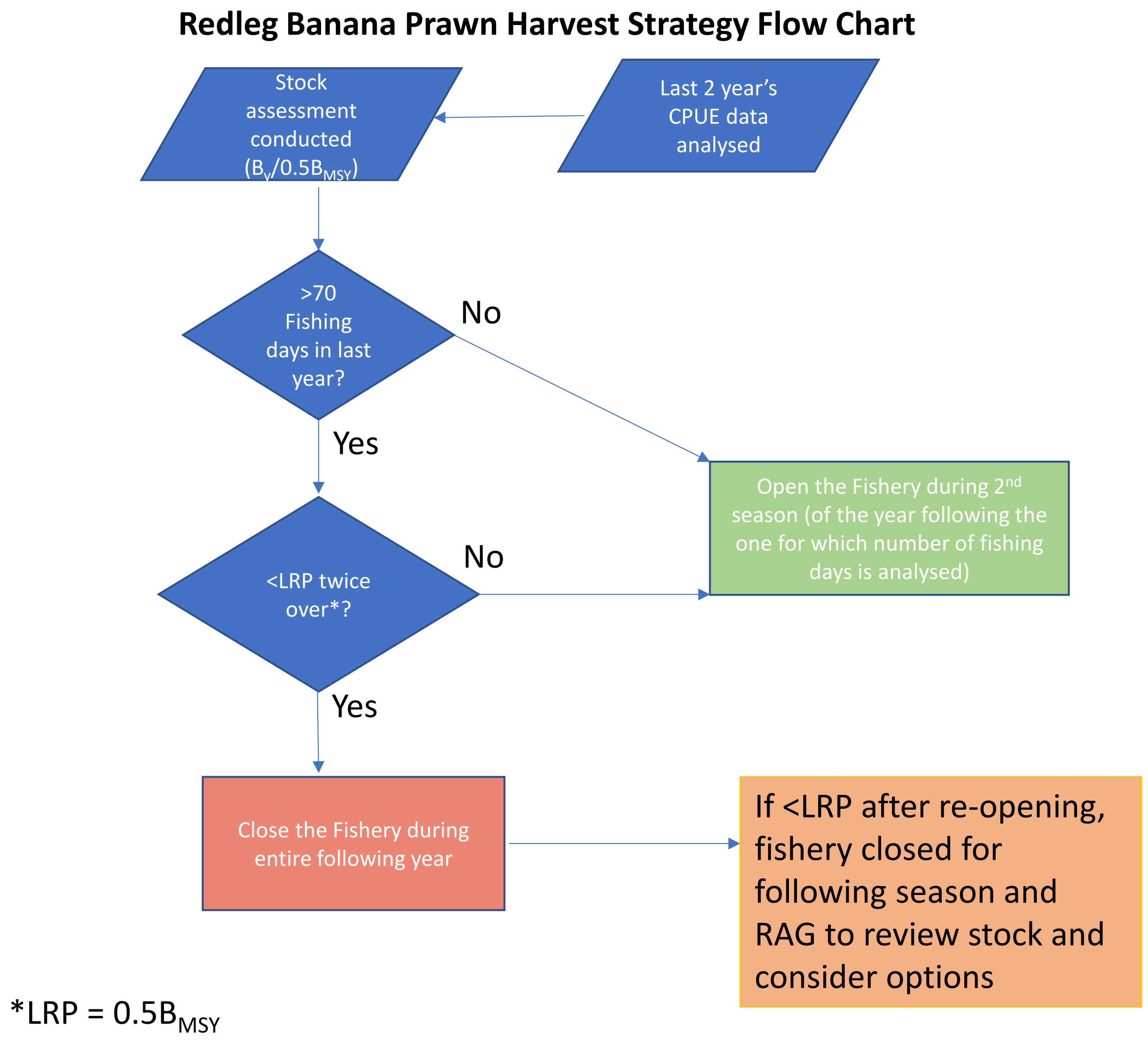
Where θ_{y*} is the fishing power for year y*, which represents the last year in the series (i.e. fishing power is held constant at the most recent level for future projections).

Accounting for non-stock assessment years

The revised harvest strategy (Appendix 2) means that in some years it won't be necessary or advisable to conduct an updated stock assessment for the current year. Once sufficient data become available in a future year, the stock assessment will be updated to inform on the status of the redleg banana prawn stock as well as to provide a TAE. Under this scenario, the model will still use as input the total catch and effort recorded for the non-assessment years but will not fit to the CPUE estimates for the non-assessment years given these will be based on fewer than the minimum number of boat days (*nmin*) considered to provide a reliable index. This in turn means that the stock assessment won't use any fishing power estimates for those years either, even though a continuous fishing power series may be estimated for all years up until the last year for which data are available for the assessment. However, the last year's fishing power estimate will account for any changes in fishing power that have occurred since the last assessment year.

The stock assessment model will therefore have a gap in the input CPUE series and although the model is able to accommodate for this by only fitting to years for which reliable data are available, this means that there may be greater uncertainty associated with the current year's assessment of resource status.

Appendix 2. Redleg Banana Prawn Harvest Strategy Flow Chart



*# – **Data sufficient year** means a year where a minimum of nmin=70 fishing boat days has been achieved and therefore sufficient data are available to run the assessment.*

1 – The minimum number of fishing boat days required to run the assessment is 70 days over the full fishing year.

2 – If data has been provided for <u>less</u> than 70 fishing boat days during the full fishing year, then fishing will be allowed for the second season.

3 – If the Redleg Banana Prawn stock size falls below the LRP for two successive data sufficient years, then the TAE is zero for a year (no fishing in the following year). The maximum number of *years between two successive data sufficient years is four, as this Harvest Strategy is reviewed every five years.*

4 – If the LRP is <u>not</u> triggered in two successive data sufficient years, then fishing will be allowed for the second season.

5 – If the LRP is triggered immediately following a fishery closure (due to consecutive breaches of the LRP), then the TAE is zero for a year (no fishing in the following year) and the NPRAG will review the stock and recommend a course of action.

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