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Stock assessment of Red Endeavour Prawns (*Metapenaeus ensis*) and Blue Endeavour Prawns (*M. endeavouri*) in the Northern Prawn Fishery using a Bayesian approach

Final Report

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Executive summary

Red Endeavour Prawns (*Metapenaeus ensis*) and Blue Endeavour Prawns (*M. endeavouri*) are harvested in the Northern Prawn Fishery (NPF), predominantly in the Tiger Prawn component of the fishery. In this staged project, we have successfully modelled growth of Red Endeavour Prawns, and developed statistical models for CPUE standardisation and fishing power estimation for both Red and Blue Endeavour Prawns. The current report describes the stock assessment for both Red and Blue Endeavour Prawns.

Endeavour Prawns in the NPF are relatively data-poor, compared to targeted Grooved Tiger Prawn (*Penaeus semisulcatus*) and Brown Tiger Prawn (*P. esculentus*). A lack of biological and fisheries data, for example, maturity at size, natural mortality, spawning patterns, availability, and catchability, prevented application of data-rich, shorter time step models to Endeavour Prawn stocks. As such, the existing Blue Endeavour Prawn assessment adopts a biomass dynamics model (BDM, *aka* surplus production model) at an annual time step. Biomass dynamics models require less information and assumptions and avoid a need to estimate influential parameters such as stock-recruitment relationships, steepness, annual and weekly recruitments, gear selectivity, spawning biomass, etc. We adhered to the Blue Endeavour Prawn approach and adopted Bayesian BDM for both Red and Blue Endeavour Prawns.

We explored various scenarios and options in regard to spatial structure, fishery history, and modelling techniques. For each species, we had the following scenarios:

- Two alternative spatial treatments: one assuming a single stock in the whole NPF and the other assuming four independent sub-stocks: (1) Outside GoC, (2) Groote, (3) Vanderlins, and (4) Weipa.
- Two catch series: Since the fishing season in the NPF has changed substantially over time, there are concerns that prawns are harvested at different life stages from year to year and that this may impact population dynamics differently. To address this question, in addition to using the nominal (raw) catch from the logbooks in the BDM, we used adjusted catch by converting catches in months other than August to equivalent weight in August based on growth and mortality.
- Three alternative Bayesian priors: non-informative, vaguely-informative, and a new data-driven priors. The new approach is a multi-pass Bayesian estimation (MBE) using posterior-as-prior.
- Two options for including abundance index: one using both fishery CPUE and scientific survey index and the other using fishery CPUE alone.
- Two Bayesian model structures: a traditional Bayesian model and a hierarchical Bayesian model.

For the single stock assessments we focused on MBE prior method because of its superior performance. Hierarchical Bayesian models were used in the multi-stock assessments. We focussed on the models using raw catch data since the estimated stock status using adjusted catch did not show marked difference from raw data for major management quantities. As Endeavour Prawn CPUE standardisation includes fisheries data up to 2020, the results presented in this report are based on data from 1970 to 2020.

Red Endeavour Prawns treated as a single stock: the posterior median unfished biomass was 4,262 mt (95% credible interval between 3,616 and 5,038 mt); the median maximum sustainable yield (*MSY*) 491 mt (95% CI 405—597 mt); the median intrinsic population growth rate 0.46 yr^{-1} (95% CI 0.41—0.51 yr^{-1}); and the median fishing mortality at *MSY* (F_{msy}) 0.23 yr^{-1} (95% CI 0.21—0.26 yr^{-1}). The median B_{2020}/B_{msy} was 1.20 (95% CI 0.77—1.76) and median F_{2020}/F_{msy} 0.21 (95% CI 0.14—0.35), suggesting the Red Endeavour Prawn stock was unlikely to be overfished and overfishing was not occurring in 2020.

Red Endeavour Prawns treated as four sub-stocks: Biomass related quantities, i.e., *K*, B_{msy}, and *MSY* varied considerably from one region to another region. The posterior median unfished stock size was 2,809, 690, 420, and 1,050 mt for Stocks 1 to 4, respectively. Estimated F_{msy} values were similar among the four stocks. Median B_{2020}/B_{msy} ratio varied from 1.08 in Region 2 to 1.88 in Region 1, and biomass in all regions were above the B_{msy} reference point. Median F_{2020}/F_{msy} ratio ranged from 0.13 in Region 4 to 0.21 in Region 3; all stocks were well below their F_{msy} benchmarks.

Blue Endeavour Prawns treated as a single stock: The biomass related quantities were larger than that for Red Endeavour Prawns. The median *K* was 9,327 mt (95% CI 7,409—11,954 mt); the median *MSY* was 953 mt (95% CI 711—1,310 mt); and the median F_{msy} 0.21 yr^{-1} (95% CI 0.16—0.26 yr^{-1}). The median B_{2020}/B_{msy} was 1.12 (95% CI 0.79—1.54) and median F_{2020}/F_{msy} 0.22 (95% CI 0.14—0.35), suggesting the stock was unlikely to be overfished and overfishing was not occurring in 2020.

Blue Endeavour Prawns treated as four sub-stocks: Biomass related quantities (i.e., *K*, B_{msy}, and *MSY*) also varied amongst the four regions but less considerable than those for Red Endeavour Prawns. The posterior median *K* was 1,790, 1,579, 2,632, and 2,306 mt for Stocks 1 to 4, respectively. *MSY* had a slightly different rank as *K*s: 199, 125, 369, and 377 mt for Stocks 1 to 4. The population growth parameter *r* varied more significantly among the four stocks than Red Endeavour Prawns, ranging from 0.32 for Stock 1 to 0.62 for Stock 4. Median B_{2020}/B_{msy} ratio was estimated as: 1.70, 0.35, 1.47, and 1.89 for Stocks 1 to 4, respectively, suggesting that although Stocks 1, 3, and 4 were above the reference point in 2020, Stock 2 is depleted (approx. 35% of unfished abundance). Despite this, the median F_{2020}/F_{msy} ratio ranged from 0.05 in Region 4 to 0.47 in Region 2, all below their F_{msy} benchmarks.

From these results, we draw the following conclusions and make corresponding recommendations:

- Blue Endeavour Prawns are more abundant than Red Endeavour Prawns. Management reference points of B_{msy} and *MSY* are nearly twice as large as that for Red Endeavour Prawns.
- Productivity, gauged by population growth rate and F_{msy}, are largely comparable between the two species, although Red Endeavour Prawns tend to have a slightly higher productivity.
- Using adjusted catch to eliminate the impact of historical varying fishing season on population by converting all catches to equivalent body weight and population size in August amplifies biomass-related quantities (e.g., *K*, B_{msy} and *MSY*) but has minimal effect on rate-related quantities (e.g., *r*, F_{msy}, B_y/B_{msy}, F_y/F_{msy}, and C_y/MSY). Converting catch in months other than August to equivalent August weight involves additional uncertainties and requires more effort. While directly using raw catch and ignoring life stage of harvested prawns may be biased toward precaution, the analysis is straightforward and does not change the overall conclusion about stock status. Hence, we recommend using raw catch data in the future stock assessment.
- Assuming one single stock or multiple sub-stocks does not lead to substantial differences about general stock status. However, spatial assessments provide detailed pictures revealing subtle variations among regions, e.g., biomass of Blue Endeavour Prawns in region 2 below target reference points. We suggest that single stock assessments, which is consistent with current Tiger Prawn assessment, is sufficient to satisfy external needs such as MSC certification as well as provide NPF stock status and management advice. Spatial assessments, on the other hand, should be considered for local conservation purposes and for inspiring future research.

Keywords: Endeavour prawns, stock assessment, Northern Prawn Fishery, Bayesian, spatial model, standardised CPUE, survey index, data-driving prior, adjusted catch

1 Introduction

Two species of Endeavour Prawns are harvested in the Northern Prawn Fishery (NPF): *Metapenaeus endeavouri* (Blue Endeavour Prawns) and *M. ensis* (Red Endeavour Prawns). They are captured in the Tiger Prawn component of the fishery, composing two of the four major commercial prawn species for this fishery. Endeavour Prawns are included as byproduct in Tiger Prawn bio-economic model that provides management advice for the NPF in the form of Total Allowable Effort recommendations. Unlike the other two species targeted in the Tiger Prawn fishery (Grooved Tiger Prawn, *Penaeus semisulcatus*, and Brown Tiger Prawn, *P. esculentus*), Endeavour Prawns are relatively data-poor. The previous components of this project that have been completed include: (1) modelling growth of Red Endeavour Prawns, and (2) CPUE standardisation for both Red and Blue Endeavour Prawns (Zhou *et al.*, 2022a, 2022b, 2022c). The current report describes the stock assessments of Red and Blue Endeavour Prawns.

Assessment expertise has focussed on the two Tiger Prawn species in the NPF. Quantitative stock assessments are regularly applied to Tiger Prawns (Wang and Die, 1996; Dichmont *et al.*, 2003; Punt *et al.*, 2010). A size structure model was developed for Tiger Prawns 10 years ago and has been routinely used in biannual assessments (Punt *et al.*, 2010; Deng *et al.*, 2021). In addition, a weekly delay-difference model was developed earlier with a focus on Tiger Prawns (Dichmont *et al.*, 2003). These data-rich models generally require extensive biological and fisheries information and it is necessary to estimate many parameters. Many of these inputs are either not available or poorly known for Endeavour Prawns.

The stock of Blue Endeavour Prawns in the NPF has been assessed using a less data-intensive, age-aggregated Bayesian hierarchical production model (BHPM) with a yearly time step. The model was developed over a decade ago as adequate biological and ecological data were unavailable for Endeavour Prawns (Zhou *et al.*, 2009; Dichmont *et al.*, 2010). Previous studies that tested this model on Grooved Tiger Prawn showed that it can produce management quantities very similar to the data-demanding weekly delay-difference model (Zhou *et al.*, 2009; Dichmont *et al.*, 2010).

However, the current Blue Endeavour Prawn BHPM has several potential weaknesses. A major concern is its use of the fishing power trend estimated primarily for Tiger Prawn assessment to “standardized” nominal CPUE data. A preliminary study using a depletion model indicated that the estimated catchability coefficient of Blue Endeavour Prawns by Tiger Prawn fleet is larger than that of Grooved Tiger Prawns (Dichmont *et al.*, 2008). Although Blue Endeavour Prawn catchability tends to increase over time it is clearly not as steep as the estimated fishing power for Grooved Tiger Prawns. The results from Stage 2 confirm that fishing efficiency on non-target Endeavour Prawns differs from that of Tiger Prawns (Zhou *et al.*, 2022b).

The current Endeavour Prawn assessment models do not take into account management changes over time that may have impacted Endeavour Prawn populations. The Northern Prawn Fishery has undergone substantial changes over time due to fishery development and management interventions. From 1970 to 1985 there were few specific controls for fishing seasons, fishing effort, and fishing time. From 1987 the fishery was split into two seasons and extensive spatial closures were made ermanent. The Banana Prawn season starts in late March or early April and ends in mid-May or early June; the Tiger Prawn season is generally from early August to mid-November. Spatial and temporal closures, as well as changes in fishing season, imply that availability can vary from year-to-year and the harvested prawns may be at different life stages.

Red Endeavour Prawns are subject to the same above-mentioned issues and assumptions as Blue Endeavour Prawns. In addition, reliable estimates of growth for Red Endeavour Prawn were only recently developed in Stage 1 of the project (Zhou *et al.*, 2022c, 2022a) and have not been included in the stock assessments. No Red Endeavour Prawn specific assessment model has been developed apart from a preliminary model that uses the same model structure and priors from the Blue Endeavour Prawn model (i.e., assumed biological parameters, catchability, and carrying capacity, but applying the Red Endeavour Prawn catch and effort data) (Deng *et al.*, 2021).

In this study, we continue to adopt Bayesian production model for Red and Blue Endeavour Prawn stock assessments. The choice of simple models ensures less disruption to the current multispecies bio-economic model and avoid potential biases and uncertainties arising from borrowing or assuming a range of unknown biological and population information. We explore various scenarios and options in regard to spatial structure, fishery history, and modelling techniques. These analyses include two alternative spatial structures, two treatments of catches, three alternative Bayesian priors, two options for including abundance indices, and two Bayesian model structures. Finally, we use the results from the 4-region spatial models to evaluate performance of the bio-economic model for management application.

2 Materials and methods

2.1 Data sources and description

2.1.1 Commercial logbook data

We examined the NPF logbook records that contain catch and effort data from 1970 to 2021. There are 972,984 records of daily vessel specific fishing activities in the 52 years of history. Endeavour Prawns are captured by four fleets that “target” Brown Tiger Prawns, Grooved Tiger Prawns, Common Banana Prawns, and Redleg Banana Prawns (Figure 1). The targeted species was identified by their dominant catch in the multi-species mixed fishery. Endeavour Prawns are primarily caught in the Tiger Prawn fishery. Blue Endeavour Prawns are captured by both Brown and Grooved Tiger Prawn fleets whereas Red Endeavour Prawns are nearly exclusively captured by the Grooved Tiger Prawn fleet (Figure 1, Table 1). The two Banana Prawn fleets also capture a small amount of Endeavour Prawns. Catch of Endeavour Prawns increased from the beginning of the fishery to a peak in the early 1980s (Table 2). Overall, catch of Blue Endeavour Prawns is larger than Red Endeavour Prawns, except in 1997 (Table 2, Figure 2). On average the catch of Blue Endeavour Prawns is more than double of Red Endeavour Prawns during the 52 years.

Fishing activities in the NPF was year-around in the early years until about 1985. The fishing season was slowly contracted and from the early 2000s the catches of Endeavour Prawns were nearly exclusive in the second fishing season (after July) (Figure 6). There were always fewer catches of Endeavour Prawns in the first fishing season (before July) than in the second fishing season. Tropical prawn species, including Endeavour Prawns in the NPF, generally live less than two years and grow fast during their short life. Hence, changes in NPF management over time could result in different body size/weight in the catch from year to year.

In this study, we explored two spatial scenarios. In the first scenario, we assumed that there is only one single stock in the NPF for each species of Endeavour Prawns. This is consistent with the current Tiger Prawn stock assessment (Deng *et al.*, 2021). In the second scenario, we assumed that there are four independent stocks in the NPF for each species of Endeavour Prawns. This treatment is consistent with current Blue Endeavour Prawn stock assessment using the hierarchical Bayesian production models (Zhou *et al.*, 2009; Dichmont *et al.*, 2010).

The current stock assessment for Blue Endeavour Prawns is based on a hierarchical structure that comprises four regional (spatial) models by combining some of the Tiger Prawn Stock Regions (Figure 3). The four stocks are referred to as: (1) Outside GoC, (2) Groote, (3) Vanderlins, and (4) Weipa (Zhou *et al.*, 2009; Dichmont *et al.*, 2010). Accordingly, Endeavour Prawn CPUE standardisation has also been analyzed at two stock structure levels: (1) treating the entire NPF area as a single stock; and (2) analysing the data for each of the four Endeavour Prawn Stock Regions.

Fishing effort and catch of Endeavour Prawns varied markedly between regions. For Red Endeavour Prawn, Region 1 had the highest catch and CPUE (Table 3, Figure 4). In contrast, Blue Endeavour Prawns had higher catch and CPUE in Regions 3 and 4 (Table 4, Figure 5).

2.1.2 Standardised CPUE and fishing power for Endeavour Prawns

In Stage 2 of the project, CPUE standardisation was successfully achieved using Endeavour Prawn-specific catch within the Tiger Prawn fleet (Zhou *et al.*, 2022b). Changes in relative fishing power on Endeavour Prawns were also estimated. The results in the CPUE standardisation report were used in this study, which includes years from 1970 to 2020 (hence, the same period of data in logbook were also used, i.e., up to 2020 rather than 2021). Using either standardized CPUE or nominal CPUE corrected by fishing power had no effect on the stock assessment outcome, because standardised CPUE and nominal CPUE can be exchangeable through fishing power: $sCPUE_y = CPUE_y/FP_y$, where *sCPUE* is standardised catch rate, *CPUE* is the nominal catch rate, and *FP* is relative fishing power.

2.1.3 Commercial Catch Composition data

To investigate how body size may vary within a year, we examined the "Commercial Catch Composition data" in the ORACLE database. A joint CSIRO/industry catch-sampling programme was conducted from 1988 through 1990 (Somers, 1994). The primary objective of this catch analysis program was to obtain background data on the composition of catches in the NPF. Fishers were trained in techniques of species identification and random sampling of catches. During the fishing season, they recorded the species composition and measured body size of samples of their catches. In addition, CSIRO conducted samplings from Northern Territory Fisheries in earlier years. The database contains seven years of data (1979, 1980, 1984, 1987-1990), 39,560 measurements of Blue Endeavour Prawns, and 12,900 measurements of Red Endeavour Prawns.

Catch composition data show that carapace length of Endeavour Prawns tends to vary over time as prawns grow rapidly during their short life span. A general pattern can be seen in the monthly length distribution (Figure 7). In the early months of the year (Jan to March), the catch samples appear to be comprised of two cohorts so there are large variations in body size depending on prawn age composition. For Blue Endeavour Prawns, the young of the year-class seems to recruit into fishery starting in December (top panels of Figure 7). Average body size increases from April to November in both species and for both sexes. More rapid changes occur during July-November, likely because the catch is primarily comprised of a single cohort.

The biomass dynamics model is typically constructed at an annual time step. If the fishing season, whether open for part of the year or year-around, does not significantly change over the fishery's history, using nominal catch (i.e., actual logbook records) is preferred and conventionally accepted practice. However, as the fishing season in the NPF has varied significantly over its history, it would be sensible to take growth and natural mortality into account in population dynamics models to account for the impact of harvesting prawns at their different life stages.

We presented the temporal patterns of life history and population of Endeavour Prawns using their biological parameters. The information includes: growth for Blue Endeavour Prawns (Buckworth, 1992; Dichmont *et al.*, 2008; Punt *et al.*, 2010), growth for Red Endeavour Prawns (Zhou *et al.*, 2022a), length-weight relationship for both Endeavour Prawn species (Venables *et al.*, 2006), and natural mortality for both Endeavour Prawn species borrowed from Tiger Prawn estimates (Wang, 1999; Dichmont *et al.*, 2008). Changes in carapace length, body weight, population size, and biomass are illustrated in Figure 8. Monthly surveys suggest that Red Endeavour Prawns spawn around January (Zhou *et al.*, 2022a, 2022c). Based on the existing biological information, the prawns reach their critical age, or the peak of cohort biomass, (Quinn and Deriso, 1999) around July. Logbook information indicates that the highest catch of Endeavour Prawns has occurred in August. Therefore, we adjusted the catches in other months to the potential amount in August. We developed a catch weight conversion ratio by considering body weight increase and population decline due to natural mortality over time:

$$CR_{sp,m} = \frac{W_{sp,m=8}}{W_{sp,m}} \exp\left(-52 * M * \left(\frac{8-m}{12}\right)\right) \quad \textbf{Equ 1}$$

where W is body weight calculated from von Bertalanffy growth function (VBGF) and length-weight relationship, M (= 0.045/week) is the weekly natural mortality, m is month, and sp is species (i.e., Blue or Red Endeavour Prawns). The body weight is the average of males and females, assuming an equal sex ratio. This equation implies that at month 8 (August), $CR_{sp,8}$ = 1, i.e., catch doesn't need to be adjusted. When $CR_{sp,m}$ < 1 (e.g., July), fishery removal has a smaller impact on the population than fishing in August, while when $CR_{sp,8}$ > 1 a same amount of catch will cause a larger reduction in population biomass than fishing in August.

2.1.4 **Surveys**

Annual spawning index surveys in July/August and recruitment index surveys in January/February have been carried out in the NPF since 2002 (Ye *et al.*, 2006; Kenyon *et al.*, 2021). These surveys were designed to monitor Tiger Prawns within key regions of the Gulf of Carpentaria (GoC). However, other prawn species, including the Endeavour Prawn species, are also captured during the surveys. The timing of the surveys matches key phases of the prawns' annual life cycle (Kenyon *et al.*, 2021). In general, the "effective spawning" of commercial prawns in the GoC occurs from August to December. Postlarvae advect inshore and settle to shallow estuaries and embayments from September to March. Emigrant juveniles that contribute strongly to the subsequent fishery catch move from the inshore nursery habitats to offshore fishing grounds from November to March, particularly November to January for Banana Prawns. Once offshore, they grow and move to deeper waters. The "recruitment survey" in late January/February measures the abundance of sub-adult prawns that have emigrated recently from the nursery habitats and are found in the shallower regions of the fishing grounds early in the year. The "spawning survey" in July (August prior to and including 2004) measures the abundance and spawning condition of large adults that are found on the fishing grounds prior to the second fishing season.

The survey abundance index is calculated as the mean number of prawns per hectare weighted by the area stratum size. We obtained information on annual spawning abundance indices of adults, sub-adults, and total prawns for each species as well as their uncertainty (standard deviation, coefficient of variance, and 95% confident intervals). Survey indices are summarized in two formats: the global indices of the whole NPF area and the regional indices for each of the sub-stock areas. There are three regions in the July/August surveys: Groote, Mornington, and Vanderlins (all in the western side of the Gulf of Carpentaria, i.e., Endeavour Stock Regions 2 and 3), while six regions are surveyed in January: Groote, Karumba, Mornington, Vanderlins, and Weipa. Because the commercial fishery only captures a small amount of Endeavour Prawns in January-February but harvests the largest quantity in July/August, we used abundance indices from August surveys. Scientific surveys cover fewer regions as well as fewer grids in each region than commercial fisheries.

2.2 Population dynamics models

The standard (or conventional) formulation of the Graham-Shaefer biomass dynamics model (BDM) (Polacheck *et al.*, 1993; Quinn and Deriso, 1999) has been tested for Tiger Prawns (Zhou *et al.*, 2009) and applied to Blue Endeavour Prawns (Dichmont *et al.*, 2010). The deterministic version of the biomass dynamics model for a studied stock can be written as:

$$B_y = B_{y-1} + rB_{y-1}\left(1 - \frac{B_{y-1}}{K}\right) - C_{y-1}$$ **Equ 2**

where B is biomass (in metric tonne), r is the intrinsic growth rate, K is the carrying capacity, C is the total catch (also in metric tonne summed from all fleets), and the subscript y is year. This standard model is adopted for the current Endeavour Prawn assessment.

The assessments involve several treatments of the species and stocks. The same form of the population dynamics model is applied to: (1) Red Endeavour Prawns treated as one single stock in the NPF using nominal (raw) catch data; (2) Red Endeavour Prawns treated as one single stock in the NPF using adjusted catch by converting nominal (raw) catch in months other than August to hypothetic weight in August; (3) Red Endeavour Prawns treated as four sub-stocks in the NPF using raw catch data; (4) Blue Endeavour Prawns treated as one single stock in the NPF using raw catch data; (5) Blue Endeavour Prawns treated as one single stock in the NPF using adjusted catch by converting nominal (raw) catch in months other than August to hypothetic weight in August; (6) Blue Endeavour Prawns treated as four sub-stocks in the NPF using raw catch data.

The annual biomass values and the two key parameters (r and K) in Equation 2 were estimated by fitting the model-estimated catch-per-unit-effort (CPUE) to the observed abundance indices. Since we have two time series of "observed" abundance indices (the quotation mark here indicates that these abundance indices may not be directly observed or calculated from fisheries data, but may be estimated, e.g., through the CPUE standardisation process), one from standardised CPUE of Endeavour Prawn catch by the Tiger Prawn fleet and the other once from fishery-independent surveys, the two estimated time series of CPUE are:

$U_{com,y} = q_{com}B_y$ **(Equ 3)** for the commercial fishery CPUE, and
$U_{surv,y} = q_{surv}B_y$ **(Equ 4)** for the survey index,

where q_{com} and q_{surv} are the catchability coefficients for Tiger Prawn fleet and survey, respectively.

2.3 Assessment of a single stock using the Bayesian approach

Fishery stock assessments unavoidably involve both process errors in the biological and ecological dynamics process and observation errors in fishery and survey data. One of the advantages of a Bayesian approach is the robust capability of handling both types of errors in the state-space models. Following the common practice, we assumed that deviations about the expected biomass are log-normally distributed (Meyer and Millar, 1999; Zhou *et al.*, 2009; Winker *et al.*, 2018), i.e.:

$$B_y \sim logNormal\left(E\left[ln\left(B_y\right)\right], \tau_B\right)$$ **Equ 5**

where τ_B is the precision (the inverse of the variance) of the process error. The prior for the biomass at the start of the first year of the modelled period is assumed to be the same as for the carrying capacity K for stock.

Similarly, the "observed" catch-rate was assumed to be log-normally distributed about its expected value in common with most applications of biomass dynamics models (Polacheck *et al.*, 1993; Meyer and Millar, 1999; Zhou *et al.*, 2009; Winker *et al.*, 2020):

$U_{com,y} \sim logNormal\left(E\left[ln\left(sCPUE_y\right)\right], \tau_{Ucom}\right)$, and

$$U_{surv,y} \sim logNormal\left(E\left[ln\left(AI_y\right)\right], \tau_{Usurv}\right)$$ **Equ 6**

where *sCPUE* is the standardised CPUE of Endeavour Prawn caught by commercial Tiger Prawn fleet (Zhou *et al.*, 2022b), and *AI* is the survey abundance index. The two time-series of abundance indices are expected to exhibit different uncertainties. Hence, we specified two precision parameters, τ_{Ucom} and τ_{Usurv} for the observation error for the standardised CPUE and survey abundance index, respectively.

The biggest advantage of using Bayesian analysis perhaps is its natural way of combining prior information with data, within a solid decision theoretical framework. Past information or information from similar studies/species about a parameter can be incorporated into the Bayesian models to form a prior distribution. However, this major advantage is also the most debated topic in Bayesian analyses because there lacks a unanimous rule on how to select a correct prior. As priors can heavily influence posterior distributions, inappropriate priors might lead to biased estimations.

In the last two to three decades, Bayesian statistical methods have proliferated throughout ecology and fisheries studies. Unfortunately, few reliable guidelines for incorporating prior information exist in the ecological and fisheries literature. The common practice is to use non-informative (or diffuse) priors. Amongst many weaknesses (Lemoine, 2019), using noninformative priors can lead to failure in model convergence in cases where there are limited, conflicting, or low quality of data, and/or models with multiple parameters. This is often the case in fisheries stock assessments. Recently, (Lemoine, 2019) recommended that ecologists should abandon noninformative priors and instead should consider weakly informative priors as the "default" prior for any Bayesian model. The recommendation has been adopted in some fisheries research. For example, the commonly applied JABBA package (Just Another Bayesian Biomass Assessment) (Winker *et al.*, 2018) employs default priors for the two BDM parameters in Equ 2 as *r.prior* = c(median = 0.2, sd = 0.5), and *K.prior*= c(median = 8 * max(Catch), cv=1). Sensitivity tests show that such weak priors can significantly affect posteriors (Zhou *et al.*, 2021).

A new method to the selection of priors is a data-driven approach (Lei *et al.*, 2021, 2023). This approach, referred to as multi-pass Bayesian estimation (MBE) modifies data-cloning method (Lele *et al.*, 2007). Both data-cloning and the MBE perform repeated Bayesian updates using the same given dataset while in each iteration the priors are updated using the posteriors from the preceding one step. In the MBE the process can be repeated many times until the deviance between the posteriors and priors reduces to a predefined acceptable precision (e.g., < 0.1%).

In the single stock assessment, we investigated alternative methods to choose priors for *K* and *r*: (1) noninformative priors; (2) weak-informative priors; and (3) MBE. General specification of prior distributions are as follows:

K ~ lognormal(log(max(*C*) * 8), *cv* = 1000)	(Noninformative)
K ~ lognormal(log(max(*C*) * 4), *cv* = 1)	(Weak informative)
r ~ lognormal(log(0.46), *cv* = 1000)	(Non-informative)
r ~ lognormal(log(0.46), *cv* = 1)	(Weak informative)

Priors for other parameters were specified as:

q_{com} ~ lognormal(-10, τ = 0.0001)

q_{surv} ~ lognormal(-10, τ = 0.0001)

τ_B ~ gamma(0.001, 0.001)

τ_{Ucom} ~ gamma(0.001, 0.001)

τ_{Usurv} ~ gamma(0.001, 0.001)

The *r* prior is based on previous stock assessment on the NPF Grooved Tiger Prawns, Blue Endeavour Prawns, Black Tiger Prawns, and Torres Strait Brown Tiger Prawns (Neill and Turnbull, 2006; Zhou *et al.*, 2009, 2021; Dichmont *et al.*, 2010).

The MBE method was applied to parameter *K* only, as carrying capacity depends on habitat range, ecosystem structure, and ecological function of interested species, making it hard to construct the Bayesian prior. We used *K* posterior from the previous run as prior for the next iteration (i.e., posterior as prior, PaP). Extensive simulations affirm MBE works well so we focused on this method for single stock assessment.

2.4 Assessment of multiple stocks using Bayesian hierarchical models

Following the current stock assessment for Blue Endeavour Prawns, we also assumed a scenario of four sub-stocks in the NPF for both Red and Blue Endeavour Prawns. These sub-stocks in the four regions (i.e., Outside GoC, Groote, Vanderlins, and Weipa) were assumed to be biologically and ecologically independent, meaning there is no reproductive interaction, migration, and stock mixing. This assumption enables applying population dynamics models to each region independently:

$$\boldsymbol{B_{s,y} = B_{s,y-1} + r_s B_{s,y-1}\left(1 - \frac{B_{s,y-1}}{K_s}\right) - C_{s,y-1}} \qquad \textbf{Equ 7}$$

This model is similar to Equ 2 except each variable and parameter is stock-specific indicated by subscript *s*. However, as a same species, sub-stocks were assumed to possess similar life-history characteristics, particularly in our case the intrinsic population growth rate. As prawns are fished by the same fishing fleet, we also assumed the catchability coefficient was similar amongst the four regions. These assumptions allowed our construction of hierarchical Bayesian biomass dynamics models so that parameters *r* and *q* were drawn from their corresponding hyper-priors (Zhou *et al.*, 2009). The priors for *r* and *q* were:

r_s ~ lognormal(μ_r, τ_r)

q_s ~ lognormal(μ_q, τ_q)

Their hyper-priors are:

μ_r ~ normal(M_r, T_r)

μ_q ~ normal(M_q, T_q)

τ_r ~ gamma(0.001, 0.001)

τ_q ~ gamma(0.001, 0.001)

Where the mean M_r = log(0.46), M_q = -8.9, and variance components of the hyper-parameters, T_r and T_q, were assumed to be half- Cauchy distribution (Gelman, 2006; Zhou *et al.*, 2009). Region-specific process error, $\tau_{B,s}$, is modelled as $\tau_{B,s}$ ~ gamma(0.001, 0.001)

Since population size may be very different from one region to another region, we did not assume a hierarchical structure for *K* but used K_s ~ lognormal(log(max[$C_{s,y}$]*4), *cv* = 1), similar to one of the weak-informative prior options in the single stock assessment above. We chose max[Cs,y]*4 as median value of *K* prior because assessment of single stock above indicated that the posterior median *K* was about 4 times of maximum catch rather than the default 8 times in JABBA.

All models, including single stock models and multiple stocks hierarchical models, were implemented in the JAGS software (Plummer, 2003). We set up three Markov chains and ran 200,000 iterations of the Gibbs sampler before taking observations. We examined the samples to ensure that the simulation had stabilized and convergence had taken place. For statistical reference, we performed the sampling for an additional 100,000 iterations.

2.5 Bio-economic models

The objective of the NPF Bio-economic model (Punt *et al.*, 2011) is to maximize total discounted profit (i.e., net present value, or NPV) given the time-trajectory of effort by fishing strategy, accounting for contributions from tiger and endeavour prawns. The model projects future effort for each Tiger Prawn fishing strategy (one targeted towards Grooved Tiger Prawns and another targeted towards Brown Tiger Prawns) by optimising the NPV over a 50-year projection period and hence computes the Maximum Economic Yield (MEY) trajectory, accounting for contributions from both Tiger and Endeavour Prawns. The bio-economic model calculates effort by fishing strategy for each of the next seven years and assumes that the eighth and all future efforts equal that for the seventh projection year.

The existing Base case bio-economic model is a 3-species model (two Tiger Prawn species plus Blue Endeavour Prawns). The Red Endeavour Prawn is included in a 4-species model as a preliminary test. In the bio-economic models, Endeavour Prawns are based on a four-region spatial Schaefer biomass dynamics model and are treated as an economic byproduct, i.e., effort is not directed at the species but catches provide revenue and attract costs associated with the amount caught, such as freight and packaging (Deng et al., 2022). The existing Endeavour Prawn BHPMs employ Tiger Prawn fishing power, which has been found inadequate for Endeavour Prawns. In this section, we updated the bio-economic model using the BHPM output obtained in the current study. The bio-economic model results using both existing and new BHPMs were compared to reveal the effect of the new stock assessment. Because the standardized CPUE series and the stock assessment were conducted for the period from 1970 to 2020 in the current staged project, the bio-economic model was compared with the 2020 assessment (Deng *et al.*, 2021).

In the bio-economic model the projected catch in the future years *y* is given by:

$$\boldsymbol{C_{s,y} = FP_{s,y} B_{s,y} q_s \left(E^{g}_{s,y} + E^{b}_{s,y}\right)} \qquad \textbf{Equ 8}$$

where $FP_{s,y}$ is the first week fishing power in stock region *s* of the future year *y* relative to 1993, q_s is the Endeavour Prawn catchability of region *s*, $E^{g}_{s,y}$ and $E^{b}_{s,y}$ are the fishing effort from two Tiger Prawn fishing fleets in region *s*.

To be consistent with the existing bio-economic model, the hierarchical multi-stock biomass dynamics models developed in this report were adopted for both Blue Endeavour Prawns and Red Endeavour Prawns.

The bio-economic model took 1,000 samples of relevant parameters from the outputs of the spatial models. The results include annual biomass, intrinsic rate of population growth, carry capacity, catchability, the variance of the process error, and Endeavour Prawn fishing power series estimated in Stage 2 of the project. From these 1,000 simulations the bio-economic model produced average catch values that contributed to the total revenue in either the 3-species (i.e., two Tiger Prawn species and Blue Endeavour Prawns) or the 4-species sensitivity test model (two Tiger Prawns and two Endeavour Prawns).

3 Red Endeavour Prawn assessment results

We presented the assessments on Red Endeavour Prawns first as this species is the major concern in the NPF management and the primary objective of this report.

3.1 One stock, raw catch

In this scenario, we treated the Red Endeavour Prawns in the whole NPF as one single stock. The catches in the logbooks were directly used in the biomass dynamics model (Equ 2). We tested multiple modelling options, including a classic Bayesian method with alternative priors and the new Bayesian method to derive data-driven priors.

3.1.1 Classic Bayesian approach

Non-informative priors

Before this study we had little knowledge about the key parameters in model Equ 2 for Red Endeavour Prawns. Hence, we first applied the common practice in Bayesian modelling of using non-informative priors for parameters *K* and *r*. Uncertainty was expressed in coefficient of variance, for example, *K.prior* ~ lognormal(median = log(max(C_y)*8), *cv* = 1,000), and *r.prior* ~ lognormal(median = log(0.46), *cv* = 1,000). The three MCMC chains had a poor convergency even after 200,000 iterations. The Gelman-Rubin diagnostic statistic *Rhat* ranged from 1.00099 to 1.44881 with a mean of 1.16208 for all parameters. *Rhat* greater than 1 suggested that chains had not converged well for most parameters. The posteriors of some parameters appeared to be unrealistic and highly uncertain (Table 6), with a median *K* = 11,954 (mt), *cv*[*K*] = 1.58, and cv for *MSY*, q_{com} and q_{surv} were all greater than 100%. The posterior for the intrinsic population growth parameter was more realistic, with a median *r* = 0.335 but relatively large *sd*[*r*] = 0.198 and and *cv*[*r*] = 0.60.

Weakly-informative priors

Because of a range of issues with non-informative priors, using weakly-informative priors is encouraged in ecological studies (Lemoine, 2019). We explored extensive choices and included results of two alternatives in Table 6. One used *K.prior* ~ lognormal(median = log(max(C_y)*8), *cv* = 1), and *r.prior* ~ lognormal(median = 0.4, *cv* = 1), which achieved a better convergence and smaller uncertainties than using non-informative priors. Assuming *cv* = 1 is a common practice in fisheries analyses and was adopted as the default value in the JABBA package. However, such a weak-prior can significantly affect posteriors. We tested various values and found that as median *K.prior* increased, the *K.posterior* followed the increasing pattern while *r.posterior* declined systematically. A second example only changed median *K.prior* to log(max(C_y)*4), which resulted in a smaller *K.posterior* and a large *r.posterior* than when median = log(max(C_y)*8) (Table 6).

3.1.2 Multi-pass Bayesian estimate (MBE) using posterior-as-prior

Problems of using non-informative and weak-informative priors motivated us to seek novel approaches. Unlike the traditional Bayesian method with one Bayesian update, MBE improved model performance by reducing both bias and variance for all parameters (Figure 9). The posteriors of the first model run could be very inaccurate but after several repetitions posteriors stabilized to a narrow range. The output of the final model run at the acceptable precision was saved for parameter inference.

Model diagnostics

The final MBE model run produced a neat convergence from three MCMC chains. The Gelman-Rubin diagnostic statistic *Rhat* was between 1.00099 and 1.00566 for all parameters, very close to 1.0, suggesting that the length of the burn-in and the number of subsequent cycles is sufficient for the results to form the basis for inference. For the commercial standardised CPUE, the majority of residuals were distributed around zero but the model under-estimated catch rate in some years when there were very large catch rates (Figure 11). There were only 15 years of survey index so the general trend was less clear. However, it appeared that the fitting to the survey index series showed a temporal trend where the model tended to underestimate abundance index in two early years (2002 and 2007) but overestimated abundance index in four recent years (2012, 2014, 2018, 2020). Anomalies in commercial standardised CPUE were likely mainly due to recruitment variations while anomalies in the survey index were more likely due to limited spatial coverage of July/August spawning surveys.

Fishery and management parameters

We presented posteriors for several key parameters with management interest (Table 8). The median unfished biomass (carrying capacity) was 4,262 mt (95% credible interval between 3,616 and 5,038 mt). The median maximum sustainable yield (*MSY*) was 491 mt (95% credible interval between 405 and 597 mt). Uncertainty, expressed as a cv was 8.5% and 10% for the two quantities, respectively. The median intrinsic population growth rate was 0.46 yr^{-1} (95% credible interval between 0.41 and 0.51 yr^{-1}), which is relatively precise (cv[r] = 5.5%). Fishing mortality at *MSY*, F_{msy} was a half of r, i.e., median[F_{msy}] = 0.23 yr^{-1} (95% credible interval between 0.21 and 0.26 yr^{-1}). Catchability coefficients were more uncertain (cv = 16.6% for Tiger Prawn fleet and 24.8% for survey vessel). The median of $6.68*10^{-6}$ for q_{com} and $3.02*10^{-5}$ for q_{surv} cannot be directly compared with each other, as they should be considered with the values and units of the corresponding abundance indices.

Three time series quantities measured in the last year (2020) relative to their management reference points were also included in Table 8. The median B_{2020}/B_{msy} was 1.20 (95% credible interval between 0.77 and 1.76), suggesting the stock is unlikely to be overfished. Similarly, F_{2020}/F_{msy} was 0.21 (95% credible interval between 0.14 and 0.35), well below 1, indicating strongly that overfishing was not occurring. Again, C_{2020}/MSY was 0.26 (95% credible interval between 0.21 and 0.31), also well below 1.

The temporal trends of catch, catch rate, biomass, and fishing mortality revealed how the Tiger Prawn fishery had impacted the Red Endeavour Prawn population (Figure 12). There were only 6 years when catch was greater than the median *MSY*. The abundance index pane in Figure 12 indicates that the Bayesian model fitted the standardised fishery abundance index fairly well for most years but was less ideal for the survey index. One potential reason is that scientific surveys, which take place before commercial fishing season, cover fewer regions and grids than the Tiger Prawn Fishery and may be inadequately represent the abundance of entire NPF area.

The most important message is perhaps in the two lower panels in Figure 12. The biomass trajectory showed that the stock was below median B_{msy} in between middle 1980s and middle 1990s and again in later 2000s. However, biomass had been above the median B_{msy} since 2010. There were only three years in the early 1980s when fishing mortality was greater than F_{msy}. Fishing mortality had remained low since 2000.

3.2 One stock, adjusted catch to weight in August

3.2.1 Converting catch in other months to catch in August

Using the biological information (Table 5) from other studies, we derived catch conversion ratio in Table 7 to convert nominal (raw) catch in other months to hypothetical weight in August. In this exercise, the weight conversion ratio was calculated for all months except Jan, Feb, and March when the fishery may have captured two cohorts, a new age-class younger than 1 yr old and an older age-class greater than 12 months old. It was difficult to know the proportion of each age-class, so we simply assumed that the conversion ratio equals to that in April. Since catches in these three months were insignificant, the assumption should have minimal influence on the results.

Because the critical age of Red Endeavour Prawns occurred in July, catch in month other than July was inefficient in terms of fishery yield. When catches were adjusted to body weight in August, the potential removal from the population in most months was greater than its actual raw catch. Therefore, the estimated "adjusted catch" was greater than the raw catch recorded in the logbooks (Figure 13). During the 51 years from 1970 to 2020, relative change of adjusted catch (= (Adjusted catch – Raw catch)/Raw catch) ranged from 12.3% to 30.6% with an average of 19.6% (Table 9). Since fishing season was longer in the early years than in the later years, the adjusted catch tends to become less critical over time (Figure 14).

3.2.2 Result of MBE method

We also tested non-informative priors and weakly-informative priors for the Red Endeavour Prawn model using the adjusted catch. The drawback was the same as for the model using raw catch data. Hence, we have only reported the results using the MBE method for the model with the adjusted catch.

The residual patterns and the posterior distributions of K, r, q_{com}, and q_{surv} were very similar to that from the model using raw catch data (i.e., Figure 10, Figure 11).

As expected, the estimated biomass related quantities were larger than that from the model using raw catch data because of the inflated adjusted catch (Table 8). For example, the median K was 5,110 mt (95% credible interval between 4,363 and 5,993 mt), 19.9% of greater than median[K] from the model using the raw catch. This was almost the same amount of deviation between the adjusted catch and raw catch in Table 9. The median MSY was now 581 mt, 18.3% greater than that of the model using raw catch. Other parameters, including r, q, F/F_{msy}, and C/MSY were comparable with those from the model using raw catch. However, biomass was slightly less optimistic. The median B_{2020}/B_{msy} was 1.10 (95% credible interval between 0.71 and 1.65). The temporal trends of catch, catch rate, biomass, and fishing mortality were nearly identical to those from the model using raw catch (Figure 15), although with one more year when catch was just above the median MSY.

3.3 Assessment of multiple stocks

Analyses using the raw and adjusted catch above indicate similar results and stock status. Therefore, in the scenario of assuming four independent stocks, we only presented the analysis of using raw catch data.

The Bayesian production models differ between one stock assessment and multiple stock assessments. With multiple stocks, a Bayesian hierarchical structure can be established. Here we assumed the intrinsic population growth rate r and the catchability coefficient q were comparable among the four stock regions and were drawn from common statistical distributions specified by hyper priors. However, the carrying capacity K could vary substantially between stock areas so it didn't have a hierarchical structure. Survey indices were not included in the model because they came from three stock regions that only match two of the four Endeavour stock regions. There was no July/August surveys in regions outside of Gulf of Carpentaria and the eastern side of the Gulf.

3.3.1 Bayesian hierarchical model diagnostics

Due to the hierarchical approach, we were unable to use the MBE method for multiple stocks. Consequently, model convergence from three MCMC chains was more difficult. The Gelman-Rubin diagnostic statistic *Rhat* was between 1.00095 and 1.31141 with a mean of 1.07819 for all parameters. Although these values were close to 1.0, they were less optimal than that for the single stock using the MBE technique. Amongst the key parameters, the catchability coefficient was more uncertain than K and r (Figure 16). Residuals did not show problematic patterns (such as temporal trends), although the model under-estimated some years when there were very large catch rates (Figure 17). Model fitting didn't show obvious superior or inferior performance for any particular stock.

3.3.2 Production model output for Red Endeavour Prawn in four stock regions

The results from the hierarchical Bayesian models showed similarity in some parameters but dissimilarity in other parameters among Red Endeavour Prawns' four stock regions. Biomass related quantities, i.e., K, B_{msy}, and *MSY* varied considerably from one region to another region (Table 10). For example, the posterior median unfished stock size was 2,809, 690, 420, and 1,050 mt for Stocks 1 to 4, respectively. B_{msy} and *MSY* followed the same ranks and were in accordance with the catch history in the four regions (Table 3). The rate parameters, i.e., r, F_{msy}, and q, were similar among the four stocks. The measurement of stock status was perhaps the most interesting and important result. Median B_{2020}/B_{msy} ratio varied from 1.08 in Region 2 to 1.88 in Region 1, suggesting Red Endeavour Prawns were depleted more heavily in Region 2 but biomass in all regions were above the B_{msy} reference point. Median F_{2020}/F_{msy} ratio ranged from 0.13 in Region 4 to 0.21 in Region 3, all well below their F_{msy} benchmarks.

Comparing to the one stock scenario in Table 8, we observed some deviations between the two assessments. The summed median K (also summed B_{msy}) from the four stocks was 17% greater than the K value in the single stock assessment (5,006 mt vs. 4,261 mt). The median summed *MSY* was only 4% greater than *MSY* from the single stock assessment (509 mt vs. 491 mt). This was due to a smaller median average of r over the four stocks than the single stock assessment (0.398 yr^{-1} vs. 0.461 yr^{-1}). Both biomass status and fishing mortality status were better off when four stocks were assumed, the average median B_{2020}/B_{msy} was 13% higher while the average median F_{2020}/F_{msy} -23% lower than the corresponding measurements in the single stock assessment. Nevertheless, the overall conclusions from the two alternative treatments were the same: Red Endeavour Prawns were not overfished and overfishing was not occurring.

Parameter uncertainties (i.e., sd in Table 10) were larger than those in the single stock assessment (sd in Table 8). For example, the coefficients of variance of the summed K and *MSY*, and the mean r and q across the four stock regions were 36.1%, 41.1%, 34.3%, and 50.2%, respectively, compared with cv[K] = 8.5%, cv[*MSY*] = 10.0%, cv[r] = 5.5%, and cv[q_{com}] = 16.6% in the single stock assessment.

Time series trajectories of catch/*MSY*, CPUE fitting, biomass/B_{msy}, and fishing mortality/F_{msy} can be graphically compared between the four stock regions from Figure 18 to Figure 21. Although none of the four stocks was overfished in the last year we assessed (2020), biomass had been below B_{msy} over the NPF history, particularly in stock region 4.

3.3.3 **Results of the bio-economic model for Red Endeavour Prawns**

Red Endeavour Prawns were included in the 4-species sensitivity test model. The new stock assessment led to a less volatile stock status measured by both S_y/S_{msy} and S_y/S_{mey} than the existing BHPM (Figure 22). Although the temporal trajectories of the two ratios showed similar patterns between the existing and new BHPM outputs, S_y/S_{msy} and S_y/S_{mey} from the new assessment fluctuated around the 100% line in most years, while those from the existing assessment indicated more depleted status since 1980s. Stock status in the final year of the assessment, i.e. S_{2019}/S_{msy} and S_{2019}/S_{mey}, remained unchanged between the two assessment models and were both above 100% (Table 11). However, for the future year projections, S_y/S_{msy} and S_y/S_{mey} from the new assessment declined rapidly to a level lower than those from the existing assessment (Figure 22, Table 11).

The projected nominal fishing efforts had only a minor difference between the existing bio-economic model and the current assessment (Figure 22). However, the current new assessment resulted in a lower projected catch than the existing model.

4 Blue Endeavour Prawn assessment results

The same model and technique for the Red Endeavour Prawns were applied to Blue Endeavour Prawns. Model performance was similar to that of Red Endeavour Prawns. In the single stock scenario, we focused on the results of the MBE method.

4.1 One stock, raw catch

4.1.1 **Model diagnostics**

As for the Red Endeavour Prawn model, the final MBE model run produced a neat convergence from three MCMC chains. Good model convergency can be seen from the distributions of three MCMC chains for parameters K, r, q_{com}, and q_{surv} (Figure 23). Gelman-Rubin diagnostic statistic *Rhat* was between 1.00099 and 1.00464 for all parameters. For the commercial standardised CPUE, the majority of residuals are distributed around zero but the model, like for Red Endeavour Prawns, also under-estimated a few years when actual catch rates were very high (Figure 24). The fitting to survey index was better than that for Red Endeavour Prawns and with no noticeable temporal trend.

4.1.2 **Fishery and management parameters**

Posteriors for key management parameters are presented in Table 12. The biomass related quantities were larger than those for Red Endeavour Prawns. For example, the median K was 9,327 mt (95% credible interval between 7,409 and 11,954 mt), twice as large as Red Endeavour Prawn carrying capacity. The median maximum sustainable yield (*MSY*) was 953 mt (95% credible interval between 711 and 1,310 mt). Uncertainty, expressed as cv was 12.3% and 15.8% for the two quantities, respectively. The median intrinsic population growth rate was 0.41 yr^{-1} (95% credible interval between 0.33 and 0.51 yr^{-1}), with a comparable relative precise (cv[r] =11.5%). The median [F_{msy}] was 0.21 yr^{-1} (95% credible interval between 0.16 and 0.26 yr^{-1}). Catchability coefficients were slightly more uncertain (cv[q] = 18.9% for Tiger Prawn fleet and 19.9% for survey vessel). The median of $7.17*10^{-6}$ for q_{com} and $8.92*10^{-4}$ for q_{surv} were larger than that for the Red Endeavour Prawns. The scientific surveys were particularly more efficient in catching Blue Endeavour Prawns than Red Endeavour Prawns—the former q_{surv} was nearly 30 times of that for the latter.

Stock status in the last year (2020) was within safe zone (Table 12). The median B_{2020}/B_{msy} was 1.12 (95% credible interval between 0.79 and 1.54), suggesting the stock is unlikely to be overfished. F_{2020}/F_{msy} was 0.22 (95% credible interval between 0.14 and 0.35), nearly identical to fishing mortality status for Red Endeavour Prawns. Again, C_{2020}/MSY was low and similar to Red Endeavour Prawns (a median of 0.25 and 95% credible interval between 0.18 and 0.33).

The time series of catch, catch rate, biomass, and fishing mortality were somewhat different from those for Red Endeavour Prawns (Figure 25). There were 9 years when catch was greater than the median *MSY*. The model fitted both fishery and survey abundance indices better than that for Red Endeavour Prawns. The biomass trajectory shows that the stock was below median B_{msy} only for a few years in late 1980s to early 1990s. There were only four years in the early 1980s when fishing mortality was greater than median F_{msy}.

4.2 One stock, adjusted catch to August

4.2.1 **Converting catch in other months to catch in August**

Similar to Red Endeavour Prawns, we converted raw catch in other months to hypothetical weight in August (Table 9). The estimated "adjusted catch" was also greater than the raw catch recorded in the logbooks (Figure 13) but the relative change of adjusted catch (= (Adjusted catch – Raw catch)/Raw catch) was lower than that for Red Endeavour Prawns, ranging from 4.7% to 19.1% with an average of 10.5% (Table 9). Similarly, due to change in fishing season, the adjusted catch tended to deviate less from raw catch over time (Figure 14).

4.2.2 Result of one stock assessment based on adjusted catch

Compared to using raw catch in the production model, using adjusted catch had limited effect on the overall estimation and pattern for most parameters. The major difference was a higher K and B_{msy} (16% greater than the model using raw catch) (Table 12). Interestingly, posterior median r was 0.37, about 10% smaller than the model using raw data (but noting negative correlation between K and r). Like Red Endeavour Prawns, using adjusted catch led to a slightly less optimistic biomass status. The median B_{2020}/B_{msy} was 1.06 (95% credible interval between 0.73 and 1.47), compared to 1.12 when raw data were used. The temporal trends of catch, catch rate, biomass, and fishing mortality were similar to those from the model using raw catch (Figure 26).

4.3 Assessment of multiple stocks

Similar to multiple stocks of Red Endeavour Prawns we also only presented the analysis of using raw catch data for Blue Endeavour Prawn multiple stock assessment. The formulation of the Bayesian production model was the same as for the Red Endeavour Prawns: a Bayesian hierarchical structure was assumed for intrinsic population growth rate r and catchability coefficient q but non-hierarchical structure for carrying capacity K. Survey indices were also excluded in the model due to their mismatch with the four Endeavour stock regions.

4.3.1 **Model diagnostics**

The model converged slightly better than the Red Endeavour Prawn model, with Gelman-Rubin diagnostic statistic Rhat varying between 1.00095 and 1.32294 with a mean of 1.03225 for all parameters. Amongst the key parameters, three MCMC chains converged fairly well for K and r, whereas the catchability coefficient was again more uncertain (Figure 27). Residuals did not show problematic patterns and appeared to be less spread than that of Red Endeavour Prawns (Figure 28). The model performed similarly across the four stocks and it was difficult to rank their performance.

4.3.2 **Model output for four Blue Endeavour Prawn stocks**

The results from the hierarchical Bayesian models also showed similarity in some parameters but dissimilarity in other parameters among Blue Endeavour Prawns' four stock regions. Biomass related quantities (i.e., K, B_{msy}, and *MSY*) varied amongst the four regions but less so than those for Red Endeavour Prawns (Table 13). For example, the posterior median K was 1,790, 1,579, 2,632, and 2,306 mt for Stocks 1 to 4, respectively. *MSY* had a slightly different rank as Ks: 199, 125, 369, and 377 mt for Stocks 1 to 4, respectively. Interestingly, actual harvest was inconsistent with stock size and the estimated *MSY* in these regions: Region 1 had a smallest amount of catch while Region 3 had the largest catch in each of the 51 years of the fishery history (Table 4). The population growth parameter *r* varied more significantly among the four stocks than Red Endeavour Prawns, ranging from 0.32 for Stock 1 to 0.62 for Stock 4. Median B_{2020}/B_{msy} ratio was estimated as: 1.70, 0.35, 1.47, and 1.89 for Stocks 1 to 4, respectively (Table 13). These values suggested that although Stocks 1, 3, and 4 were in good shape in 2020, Stock 2 might have been depleted to around 35% of unfished abundance. In contrast, median F_{2020}/F_{msy} ratio was low for all stocks, ranging from 0.05 in Region 4 to 0.47 in Region 2, all below their F_{msy} benchmarks.

Comparing to the one stock scenario in Table 12, there were also some deviations between the single and multiple stock assumptions for Blue Endeavour Prawns. The summed median *K* (also summed B_{msy}) from the four stocks (Table 13) was -11% smaller than the *K* value in the single stock assessment (8,348 mt vs. 9,327 mt) (Table 8). The median summed *MSY* was 15% greater than *MSY* from the single stock assessment (1,097 mt vs. 953 mt). This was due to a larger median average of *r* from the four-stock model than the single stock assessment (0.495 yr^{-1} vs. 0.409 yr^{-1}, Tables 13 and 8). Although biomass in Region 2 may have been overfished, the average median B_{2020}/B_{msy} across 4 stocks was still 20.5% higher than the single stock model. The average median F_{2020}/F_{msy} was also higher than that from the single stock model but only 6% higher. If we averaged estimates over four stocks, the conclusions from the two alternative treatments were the same: Blue Endeavour Prawns were not overfished and overfishing was not occurring in 2020.

Similar to the Red Endeavour Prawn assessments, parameter uncertainties were larger than those in the single stock assessment (see sd in Tables 12 and 13). For example, the coefficients of variance of the summed *K* and *MSY*, and the mean *r* and *q* across the four stock regions were 16.1%, 22.1%, 23.8%, and 24.3%, respectively, compared with cv[*K*] = 12.3%, cv[*MSY*] = 15.8%, cv[*r*] = 11.5%, and cv[q_{com}] = 18.9% in the single stock assessment. However, differences in parameter uncertainties between the single and multiple stock assessments were smaller than those differences in the Red Endeavour Prawn assessments.

Time series trajectories of C_y/MSY, CPUE fitting, B_y/B_{msy}, and F_y/F_{msy} for each stock were presented in Figure 29, Figure 30, Figure 31, and Figure 32. Stocks 1, 3, and 4 were in good shape in most years but biomass estimates of Blue Endeavour Prawns in Region 2 were below B_{msy} for an extensive period.

4.3.3 Results of the bio-economic model for Blue Endeavour Prawns

Blue Endeavour Prawns were tested in both the 3-species model and 4-species sensitivity test model. Similar to Red Endeavour Prawns, the new stock assessment led to a less volatile stock status measured by both S_y/S_{msy} and S_y/S_{mey} than the existing BHPM (Figure 33). Although the temporal trajectories of the two ratios showed similar patterns between the existing and new BHPM outputs, S_y/S_{msy} and S_y/S_{mey} from the new assessment oscillated closer to the 100% line in most years, while those estimates from the existing assessment were below 100% for nearly all years since 1980s. Some minor differences existed between the 3-species model and the 4-species model for the same species (Table 11, Table 14), but in the current assessment, the final year stock status was improved (i.e., from below 100% to above 100%) from the existing results in both the 3-species model and 4-species model. In the future year projections, S_y/S_{msy} and S_y/S_{mey} from the new assessment were slightly higher than in the existing assessment (Figure 33Figure 22).

The projected nominal fishing efforts also had only a minor difference between the existing bio-economic model and the current assessment (Figure 33), similar to Red Endeavour Prawns. However, the current new assessment resulted in a lower projected catch than the existing model.

5 Discussion

This study presents the third and the final report for the project *"Red Endeavour Prawn assessment – further potential improvements*" (see (Zhou *et al.*, 2022c, 2022b) for the other two reports). We incorporated results from the two earlier reports, as well as other fisheries and biological information into stock assessment models for both Red and Blue Endeavour Prawns in the NPF. This is the first systematic assessment of Red Endeavour Prawns using Bayesian production models. We also extended and enhanced the existing Blue Endeavour Prawn assessment using their own standardised CPUE (i.e., not borrowing from Tiger Prawn fishing power). We explored multiple alternatives in spatial structures, types of catches, choices of Bayesian priors, sources of abundance index, and Bayesian model structure. These alternative analyses, together with uncertainty estimation in all model outputs, offer a comprehensive picture of population dynamics of and fishery impact on the Red and Blue Endeavour Prawns in the NPF. To provide a deep insight into the study, several aspects of regarding the assessments deserve some discussions.

Bayesian priors

The Bayesian approach has proliferated in fisheries research in the last two decades, particularly since several Bayesian software packages became freely available, including WinBUGS, OpenBUGS, JAGS, and Stan. The software packages allow a fully Bayesian approach using Gibbs sampling for posterior computation. In contrast with the classical frequentist approach, the Bayesian approach can easily handle realistic distributional assumptions as well as nonlinearities in state and observation equations (Meyer and Millar, 1999). Compared to classical statistics methods (i.e., Ordinary Least Squares and Maximum Likelihood), a major advantage in Bayesian statistics is to formally incorporate our prior beliefs of the parameters into the model via Bayes theorem. The prior distributions for unknown quantities are then updated to posterior distributions using the laws of probability. The use of a prior enables inclusion of expert beliefs and previous or similar studies into the current dataset. More significantly, in many data-poor cases (limited quantity of data or high uncertain data) the priors empower Bayesian models to estimate parameters when classical statistic methods fail.

Ironically, the advantage of using a prior is also the weakest point of Bayesian approach. For example, the SAS documentation on "Introduction to Bayesian Analysis Procedures" (https://documentation.sas.com/?cdcId=pgmsascdc&cdcVersion=9.4_3.3&docsetId=statug&docsetTarget=statug_introbayes_sect015.htm&locale=en) lists three disadvantages to using Bayesian analysis. The first two weaknesses relate to prior: (1) It does not tell you how to select a prior. There is no correct way to choose a prior. Bayesian inferences require skills to translate subjective prior beliefs into a mathematically formulated prior. If you do not proceed with caution, you can generate misleading results. (2) It can produce posterior distributions that are heavily influenced by the priors. From a practical point of view, it might sometimes be difficult to convince subject matter experts who do not agree with the validity of the chosen prior. (3) It often comes with a high computational cost, especially in models with a large number of parameters.

Unfortunately, in many fisheries studies there is a lack of reliable existing knowledge or expert belief about model parameters. A common practice has been using non-informative (or diffuse) priors. When the data quality is good (e.g., large sample size and low uncertainty) and the model only involved low-dimensional problems, using non-informative priors can produce excellent posteriors. However, fisheries data often contain limited observations with high process and measurement errors while the models typically deal with high-dimensional problems. Using non-informative priors may cause Bayesian models to fail to converge, high variance in posteriors distribution, and unrealistic estimation, such as in our Red Endeavour

Prawn example (Table 6). The difficulty has motivated adoption of weakly-informative priors (Lemoine, 2019) in ecological studies. Indeed, extensive applications of informative priors can be seen in fisheries literature (Meyer and Millar, 1999; McAllister *et al.*, 2001; Simon *et al.*, 2011; Winker *et al.*, 2018). Informative priors, whether strong or weak, lead to another dilemma: their significant effects on posteriors.

Recently, there has been an increasing interest in data-driven priors (Lele *et al.*, 2007; Martin and Walker, 2019; Lei *et al.*, 2021). For example, the idea of data cloning is to calculate maximum likelihood estimates and their standard errors for complex ecological models. Although the method uses the Bayesian framework and exploits the computational simplicity of the Markov chain Monte Carlo (MCMC) algorithms, it provides valid frequentist inferences such as the maximum likelihood estimates and their standard errors. The inferences are completely invariant to the choice of the prior distributions and therefore avoid the inherent subjectivity of the Bayesian approach. Alternative to this idea, one can conduct sensitivity analyses, rerunning a Bayesian analysis with progressively narrower differences between the prior and posterior distributions (Korner-Nievergelt *et al.*, 2015; Zhou *et al.*, 2021). The narrowest distribution that does not affect results is thus the best "informative" prior (Korner-Nievergelt *et al.*, 2015; Lemoine, 2019; Zhou *et al.*, 2021). The concept is essentially a maximum likelihood estimation to "let the data speak for themselves". While the model produces results asymptotic to maximum likelihood estimates, the Bayesian implementation facilitates model convergence and solves the high-dimensional models that may have no least squares solution and fail under maximum likelihood optimization. The MBE approach has been simulation tested to be able to ensure the posteriors are within the most likely range of the true parameters (Lei *et al.*, 2021, 2023).

Raw catch versus adjusted catch

In the biomass dynamics model (Equ 2), catch is the only input data. The timing of the catch determines the timing of all parameters in the model. Traditionally, fishing season was year around, so the estimated annual biomass is the average biomass each year (Quinn and Deriso, 1999). In the case of a pulse fishery, the estimated biomass is then the biomass during the short fishing season. One of the concerns with yearly time step population dynamics models arises when fishing season varies from year to year. Fisheries management in the NPF has changed over time. We show monthly catch over the NPF history in Figure 6 as a consequence of changes in fishing season. Commercial catch samples also reveal varying size composition when prawns are harvested in different months (Figure 7). We used life history information to calculate catch conversion ratios so catch in months other than August can be converted to body weight and population size in August, the month with the highest catch. Such an effort attempts to address the concern of catching prawns at different life stages causing disproportionate impact on the modelled population over time.

Converting catch in other months to weight in August enlarges the raw nominal catch (Figure 13, Figure 14). Therefore, the estimated biomass and biomass-related reference points, i.e., K, B_{msy} and MSY, are greater than these quantities from the model using raw catch data. However, using adjusted catch has insignificant effects on rate-related quantities, such as r, F_{msy}, B_y/B_{msy}, F_y/F_{msy}, C_y/MSY, as well as their time series. This outcome is similar between Red and Blue Endeavour Prawns.

We believe that models based on adjusted catch are theoretically justified when fishing season changes markedly over time and the results from such models are more realistic. However, converting nominal catch to adjusted catch involves additional uncertainties that we have not fully incorporated into the model. These additional potential biases and uncertainties come from input parameters, including natural mortality, growth parameters, spawning pattern and timing, length-weight relationship, sex ratio, and the composition of different year-classes in the catch. Considering the rate-related parameters, which are more interesting to management, are less influenced, it could be justifiable to adopt the simpler models that use raw catch data. More conservative estimates of biomass related parameters from using nominal catch may also better serve a precautious management principle.

Single stock versus multiple stocks

Spatial stock assessments have attracted increasing attention in the past decade (Punt, 2019). Increasing available data in many fisheries suggest that the dynamic pool assumption of a single homogeneous stock could be violated. In the NPF, stock assessments of Tiger Prawn species (Grooved, Brown, and Black Tiger Prawns) have been based on the assumption of one single homogeneous stock for each species (Dichmont *et al.*, 2010; Punt *et al.*, 2010; Deng *et al.*, 2021; Zhou *et al.*, 2021). For Endeavour Prawns, scientific surveys show different reproduction and recruitment patterns between the eastern regions and western regions of the Gulf of Carpentaria (Dichmont *et al.*, 2008). To account for spatial heterogeneity, the existing assessment of Blue Endeavour Prawns is based on four independent stock regions and uses biomass dynamics models. In this report, we conducted assessments for both scenarios, one treating each species in the NPF as a single stock while the other scenario assuming four independent stocks. The single stock assessment is consistent with the Tiger Prawn assessment and may provide sufficient information for the purpose of current management. The results from single stock assessments are largely supported by the combined spatial stock assessment models for both Red and Blue Endeavour Prawns. The overall conclusions from the two alternative spatial treatments are the same: Red and Blue Endeavour Prawns were not overfished and overfishing was not occurring in the last year (2020) we analysed.

On the other hand, the spatial multiple sub-stock assessments give specific and detailed results regarding each independent stock area. For both species, biomass status (B_y/B_{msy}) varied among regions. Although median B_{2020}/B_{msy} ratios were all above 1 for Red Endeavour Prawns, population in Region 2 has been depleted more heavily than in other regions. A particular concern is that Blue Endeavour Prawns, also in Region 2, may have been overfished in recent years. However, the spatial multiple sub-stock assumption led to larger uncertainties in the estimated parameters than those in the single stock assessments for both species. The Red Endeavour Prawn spatial assessment was particular uncertain, with an averaged coefficient of variation for key parameters (i.e., K, MSY, r, and q) four times greater than mean cv of the same parameters in the single stock assessment. We recognize that our spatial assessments are not rigorous enough in several aspects, including defining stock regions, determining the number of biologically genuine stocks, and a lack of interaction and movement between regions. All these questions require further research in both field ecological investigations and desktop modelling studies.

Single Tiger Prawn fleet versus two Tiger Prawn fleets

Endeavour Prawn CPUE standardisation and fishing power estimation are based on catch by one single Tiger Prawn fleet (Zhou *et al.*, 2022b). The “single Tiger Prawn fleet” model follows the practice of the Tiger Prawn fishing power analysis where the catches of Grooved Tiger Prawns, Brown Tiger Prawns, and a half of Endeavour Prawns are combined and the total catch by a single Tiger Prawn fleet form input to produce a single time series of fishing power (Dichmont *et al*., 2010). Although the two Tiger Prawns are assessed separately, where one species is treated as the target while the other one as by-catch (by-product) in each model, the two species are identified not by fishers in the logbooks but by a statistical species split model (Venables *et al*., 2006). Furthermore, both the Grooved Tiger Prawn model and the Brown Tiger Prawn model use the same fishing power estimates, i.e., fishing power changes are assumed to be the same for “target” and “by-catch” species. Earlier preliminary study shows that when the Tiger Prawn fleet is split into two fleets, assuming one is targeting Grooved Tiger Prawns while the other is targeting Brown Tiger Prawns, the changes in catchability coefficients differ between target and by-catch fleets for the two Tiger Prawns species and Blue Endeavour Prawn species (Dichmont *et al.*, 2008). The difference is conceivable because catchability is, besides technology improvement, a function of spatial availability, which likely differs between target and by-catch species. For this reason, stock assessment must be coherent with the time series of standardised CPUE or fishing power trend. There are two options: (1) standardising CPUE or modelling fishing power based on one Tiger Prawn fleet (i.e., not splitting to two species of Tiger Prawns) and using this one time series of standardised CPUE (sCPUE) or fishing power (FP) in stock assessment models; or (2) standardising CPUE or modelling fishing power based on two Tiger Prawn fleets (i.e., one targeting Grooved Tiger Prawns and the other one targeting Brown Tiger Prawns) and using this two time series of sCPUE or FP in stock assessment models.

The existing Blue Endeavour Prawn assessment is based on CPUE from two Tiger Prawn fleets adjusted by a single time series of Tiger Prawn fishing power. The current report amends this likely bias and uses sCPUE from a single Tiger Prawn fleet standardised by Endeavour Prawns' own catch data.

Comparison of two Endeavour Prawn species

Model performances are similar between Red and Blue Endeavour Prawns, demonstrated in convergency of MCMC chains, residual patterns, and parameter uncertainties. Apparent differences exist in the estimated biological and management quantities. Red Endeavour Prawns have a smaller (i.e., about one half of Blue Endeavour Prawns) carrying capacity, population size, and reference points B_{msy} and MSY than Blue Endeavour Prawns. However, it appears that Red Endeavour Prawns tend to have a slightly greater intrinsic population growth rate and the resulting F_{msy} than Blue Endeavour Prawns. Stock status, either measured by biomass or fishing mortality, are very similar between the two species. Both species were not overfished and overfishing not occurring in the last year (2020) that we analysed.

Spatial stock assessments reveal some detailed differences between the two species. Red Endeavour Prawns are most abundant in stock region 1 (Outside GoC), while Blue Endeavour Prawns are most abundant in stock region 3 (Vanderlins). Their different spatial distributions are manifested in varying management reference points B_{msy} and MSY in these regions. Biomass status also diverse in some degree. The Red Endeavour Prawn stock is not overfished in any of the sub-stocks in recent years, however, Blue Endeavour Prawns appear to have been overfished in stock region 2 (Groote) in the past 10 years.

Comparison with existing Blue Endeavour Prawn assessment model

This study has made several changes to the existing Blue Endeavour Prawn production model. Adopting Endeavour Prawn specific fishing power is the primary variation. There are also some modifications in Bayesian model settings. The existing model constructs hierarchical parameters for parameters K, r, and q across the four stock regions. However, assuming similar carrying capacity among the four regions may be untenable so non-hierarchical structure is assumed for K in the current analysis. To see how the new assessment differs from the existing, we ran the existing Blue Endeavour Prawn model and compared the results between the two. For example, the existing model yields summed median K = 6,193 mt from four sub-stocks, summed median MSY = 798 mt, and an average median r = 0.511 yr^{-1}. In comparison, the current spatial model (as well as the single stock model) yields smaller K and MSY but estimates slightly larger r. The more striking difference is the biomass status: the existing model results in $B_{2020}/B_{msy} < 1$ for three out of four sub-stocks, except stock region 4.

Conclusions and recommendations

Red and Blue Endeavour Prawn stocks in the NPF are comprehensively assessed in this study. We explored alternative scenarios regarding stock spatial structure, the effects of varying fishing season on population dynamics, and various Bayesian model settings. These models reach the following overall conclusions, which enable us to make corresponding recommendations:

- Blue Endeavour Prawns are more abundant than Red Endeavour Prawns. Management reference points of B_{msy} and MSY are nearly twice as large as those for Red Endeavour Prawns.
- Productivity, gauged by population growth rate and F_{msy}, is largely comparable between the two species, although Red Endeavour Prawns tend to have a slightly higher productivity.
- Using adjusted catch to eliminate the impact of historical varying fishing season on the populations by converting all catches to equivalent body weight and population size in August amplifies biomass-related quantities (e.g., K, B_{msy} and MSY) but has minimal effect on rate-related quantities (e.g., r, F_{msy}, B_y/B_{msy}, F_y/F_{msy}, and C_y/MSY). Converting catch in months other than August to equivalent August weight involves additional uncertainties and requires more analytical effort. While directly using raw catch and ignoring the life stage of harvested prawns might introduce a precautionary bias for biomass-related quantities, the analysis is straightforward and does not change the overall conclusion about stock status. Hence, we recommend using raw catch data in future stock assessments.
- Assuming one single stock or multiple sub-stocks does not lead to substantial differences in conclusions about general stock status for either species. However, spatial assessments provide detailed pictures revealing subtle variations among regions. We suggest that the single stock assessment, which is consistent with current Tiger Prawn assessment, is sufficient for external usage (such as MSC certification) and overall NPF management. Spatial assessments, on the other hand, should be considered for local conservation purposes and could be run intermittently to detect localized depletion. .

References

Buckworth, R. C. 1992. Movements and growth of tagged Blue endeavour Prawns, *Metapenaeus endeavouri* (Schmitt 1926), in the Western Gulf of Carpentaria, Australia. Australian Journal of Marine and Freshwater Research, 43: 1283–1299.

Deng, R. A., Hutton, T., Punt, A., Upston, J., Miller, M., Moeseneder, C., and Pascoe, S. 2021. Status of the Northern Prawn Fishery Tiger Prawn Fishery at the end of 2019 with estimated TAEs for 2020 and 2021. Report to the Australian Fisheries Management Authority, September 2021. CSIRO. Brisbane. 102 p.

Deng, R. A., Miller, M., Upston, J., Hutton, T., Moeseneder, C., Punt, A. E., and Pascoe, S. 2022. Status of the Northern Prawn Fishery Tiger Prawn Fishery at the end of 2021 with estimated TAEs for 2022 and 2023. Report to the Australian Fisheries Management Authority, October 2022. CSIRO. Brisbane. 100 p.

Dichmont, C. M., Punt, a. E., Deng, a., Dell, Q., and Venables, W. 2003. Application of a weekly delay-difference model to commercial catch and effort data for tiger prawns in Australia's Northern Prawn Fishery. Fisheries Research, 65: 335–350.

Dichmont, C. M., Deng, A. R., Punt, A. E., Venables, W. N., Ellis, N., Kompas, T., Ye, Y., *et al.* 2008. Bringing economic analysis and stock assessment together in the NPF: a framework for a biological and economically sustainable fishery. FRDC Final Report 2004/022. 228 p.

Dichmont, C. M., Deng, A. R., A.E. Punt, Venables, W. N., Pascoe, S., Zhou, S., Kompas, T., *et al.* 2010. Developing techniques to estimate total allowable catches for the NPF major prawn species. FRDC Project 2007/018 Final Report. 369 p.

Gelman, A. 2006. Prior distributions for variance parameters in hierarchical models. Bayesian Analysis, 1: 515–533.

Kenyon, R. A., Deng, R., Donovan, A. G., van der Velde, T. D., Fry, G., Tonks, M., Moeseneder, M., and Salee, K., 2021. An Integrated Monitoring Program for the Northern Prawn Fishery 2018-2021. 221 pp.

Korner-Nievergelt, F., Roth, T., von Felten, S., Guélat, J., Almasi, B., and Korner-Nievergelt, P. 2015. Prior Influence and Parameter Estimability. *In* Bayesian Data Analysis in Ecology Using Linear Models with R, BUGS, and STAN, pp. 265–278. Elsevier.

Lei, Y., Zhou, S., and Ye, N. 2021. Prior versus data: A new Bayesian method for fishery stock assessment. *In* 24th International Congress on Modelling and Simulation, pp. 43–49. Sydney, NSW, Australia, 5 to 10 December 2021 mssanz.org.au/modsim2021.

Lei, Y., Zhou, S., Ye, N., and Filar, J. 2023. Multi-pass Bayesian estimation: a robust Bayesian method. Computational Statistics. In revision.

Lele, S. R., Dennis, B., and Lutscher, F. 2007. Data cloning: easy maximum likelihood estimation for complex ecological models using Bayesian Markov chain Monte Carlo methods. Ecology Letter, 10: 551–563.

Lemoine, N. P. 2019. Moving beyond noninformative priors: why and how to choose weakly informative priors in Bayesian analyses. Oikos, 128: 912–928.

Martin, R., and Walker, S. G. 2019. Data-driven priors and their posterior concentration rates. Electronic Journal of Statistics, 13: 3049–3081.

McAllister, M. K., Pikitch, E. K., and Babcock, E. A. 2001. Using demographic methods to construct Bayesian priors for the intrinsic rate of increase in the Schaefer model and implications for stock rebuilding. Canadian Journal of Fisheries and Aquatic Sciences, 58: 1871–1890.

Meyer, R., and Millar, R. B. 1999. BUGS in Bayesian stock assessments. Canadian Journal of Fisheries and Aquatic Science, 56: 1078–1086.

Neill, M. F. O., and Turnbull, C. T. 2006. Stock Assessment of the Torres Strait Tiger Prawn Fishery (Penaeus esculentus). Department of Primary Industries and Fisheries, Queensland.

Plummer, M. 2003. JAGS: A program for analysis of Bayesian graphical models using Gibbs sampling. *In* Proceedings of the 3rd International Workshop on Distributed Statistical Computing. March 20–22, Vienna, Austria.

Polacheck, T., Hilborn, R., and Punt, A. E. 1993. Fitting Surplus Production Models: Comparing Methods and Measuring Uncertainty. Canadian Journal of Fisheries and Aquatic Sciences, 50: 2597–2607.

Punt, A. E., Deng, R. A., Dichmont, C. M., Kompas, T., Venables, W. N., Zhou, S., Pascoe, S., Hutton, T., Kenyon, R., van der Velde, T., and Kienzle, M. 2010. Integrating size-structured assessment and bioeconomic management advice in Australia's northern prawn fishery. ICES Journal of Marine Science, 67: 1785–1801. http://icesjms.oxfordjournals.org/cgi/doi/10.1093/icesjms/fsq037.

Punt, A. E., Deng, R., Pascoe, S., Dichmont, C. M., Zhou, S., Plagányi, É. E., Hutton, T., Venables, W., Kenyon, R., van der Velde, T. 2011. Calculating optimal effort and catch trajectories for multiple species modelled using a mix of size-structured, delay-difference and biomass dynamics models. Fisheries Research, 109: 201–211.

Punt, A. E. 2019. Spatial stock assessment methods: A viewpoint on current issues and assumptions. Fisheries Research, 213: 132–143. Elsevier.

Quinn, T. J., and Deriso, R. B. 1999. Quantitative fish dynamics. Oxford University Press, New York.

Simon, M., Fromentin, J. M., Bonhommeau, S., Gaertner, D., and Etienne, M. P. 2011. Investigating the performances of a Bayesian biomass dynamics model with informative priors on the Atlantic bluefin tuna. Collect. Vol. Sci. Pap. ICCAT, 66: 811–828.

Somers, I. F. 1994. Species composition and distribution of commercial penaeid prawn catches in the Gulf of Carpentaria, Australia, in relation to depth and sediment type. Marine and Freshwater Research, 45: 317–335.

Venables, W. N., Kenyon, R. A., Bishop, J. F. B., Dichmont, C. M., Deng, R. A., Burridge, C., Taylor, B. R., Donovan, A. G., Thomas, S. E., Cheers, S. J. 2006. Species Distribution and Catch Allocation: data and methods for the NPF, 2002-2004 Final Report. Final Report AFMA Project No. R01/1149. Cleveland. 171 pp.

Wang, Y. 1999. A maximum-likelihood method for estimating natural mortality and catchability coefficient from catch-and-effort data. Marine and Freshwater Research, 50: 307–311.

Wang, Y. G., and Die, D. 1996. Stock-recruitment relationships of the tiger prawns (Penaeus esculentus and Penaeus semisulcatus) in the Australian Northern Prawn Fishery. Marine and Freshwater Research, 47: 87–95.

Winker, H., Carvalho, F., and Kapur, M. 2018. JABBA: Just Another Bayesian Biomass Assessment. Fisheries Research, 204: 275–288. Elsevier. https://doi.org/10.1016/j.fishres.2018.03.010.

Winker, H., Carvalho, F., Thorson, J. T., Kell, L. T., Parker, D., Kapur, M., Sharma, R., *et al.* 2020. JABBA-Select: Incorporating life history and fisheries' selectivity into surplus production models. Fisheries Research, 222. Elsevier B.V.

Ye, Y., Kenyon, R. A., Burridge, C., Dichmont, C. M., Pendrey, R., van der Velde, T., Vance, D., Bishop, J., Donovan, A., and Zhou, S. 2006. An Integrated Monitoring Program for the Northern Prawn Fishery 2005-06. Project AFMA R05/0599 NORMAC. 229 pp.

Zhou, S., Punt, A. E. A. E. A. E., Deng, R., Dichmont, C. M., Ye, Y., and Bishop, J. 2009. Modified hierarchical Bayesian biomass dynamics models for assessment of short-lived invertebrates: A comparison for tropical tiger prawns. Marine and Freshwater Research, 60: 1298–1308.

Zhou, S., Deng, R., Hutton, T., and Miller, M. 2021. Black tiger prawn CPUE standardisation and stock assessment. Final report to Australian Fishery Management Authority. Brisbane, Australia. 91 pp.

Zhou, S., Hutton, T., Lei, Y., Miller, M., van Der Velde, T., and Deng, R. A. 2022a. Estimating growth from length frequency distribution: comparison of ELEFAN and Bayesian approaches for red endeavour prawns (Metapenaeus ensis). ICES Journal of Marine Science, 79: 1942–1953.

Zhou, S., Deng, R., Lei, Y., Miller, M., Velde, T. Van Der, and Hutton, T. 2022b. Catch rate standardisation for endeavour prawns (Metapenaeus endeavouri and M. ensis) in the Northern Prawn Fishery. Final Report to Australian Fishery Management Authority. Brisbane, Australia. 71 pp.

Zhou, S., Hutton, T., Lei, Y., Miller, M., Velde, T. Van Der, and Deng, R. 2022c. Modelling growth of red endeavour prawns (Metapenaeus ensis) using new ELEFAN and Bayesian growth models. Final report to Australian Fishery Management Authority. Brisbane, Australia. 55 pp.

Table 1. Annual catch of Blue Endeavour, Red Endeavour, and combined two species by Brown Tiger Prawn fleet, Grooved Tiger Prawn fleet, and combined Tiger Prawn fleet, respectively. Catches are in metric tonnes (mt) and the efforts are in Boat-days. These values are used to calculate nominal CPUE.

Year	Blue catch	Red catch	Combined catch	Brown effort	Blue catch	Red catch	Combined catch	Grooved effort	Blue catch	Red catch	Combined catch	Tiger effort
1970	289.5	6.2	295.7	4,481	34.4	86.1	120.5	1,482	323.9	92.3	416.2	5,963
1971	126.3	5.6	131.8	3,430	84.6	111.2	195.8	3,147	210.8	116.7	327.6	6,577
1972	165.1	3.4	168.4	4,657	48.9	130.5	179.4	2,694	214.0	133.9	347.9	7,351
1973	283.1	7.9	291.0	3,971	100.3	83.2	183.5	3,197	383.4	91.2	474.6	7,168
1974	92.9	11.8	104.7	1,320	139.4	146.1	285.6	2,173	232.3	158.0	390.3	3,493
1975	141.2	7.7	148.9	3,022	134.3	158.5	292.8	3,614	275.5	166.2	441.7	6,636
1976	193.1	9.8	202.9	3,257	244.7	264.4	509.0	4,715	437.7	274.2	711.9	7,972
1977	478.7	14.6	493.4	6,252	332.0	336.7	668.6	6,287	810.7	351.3	1,162.0	12,539
1978	530.3	16.0	546.3	8,585	390.1	255.9	646.0	10,645	920.4	271.9	1,192.3	19,230
1979	610.2	14.7	624.9	10,102	384.8	277.4	662.2	8,140	995.0	292.1	1,287.2	18,242
1980	1,005.9	30.0	1,035.9	18,399	521.5	451.6	973.1	14,662	1,527.4	481.6	2,009.0	33,061
1981	791.4	29.9	821.4	16,400	649.1	669.0	1,318.1	17,389	1,440.6	698.9	2,139.5	33,789
1982	857.3	24.1	881.4	17,274	511.2	648.0	1,159.3	16,763	1,368.5	672.2	2,040.7	34,037
1983	708.0	17.1	725.1	17,782	281.7	331.4	613.1	17,305	989.7	348.5	1,338.2	35,087
1984	683.6	13.7	697.3	15,429	459.5	445.5	905.0	17,084	1,143.1	459.1	1,602.2	32,513
1985	492.8	9.9	502.6	10,917	565.3	536.6	1,101.9	15,564	1,058.0	546.5	1,604.5	26,481
1986	323.5	6.3	329.8	12,365	200.1	203.2	403.4	15,316	523.6	209.5	733.1	27,681
1987	246.9	10.1	257.0	7,476	194.6	195.0	389.6	15,110	441.5	205.1	646.7	22,586
1988	261.4	3.4	264.8	10,550	173.3	170.2	343.5	15,875	434.7	173.6	608.3	26,425
1989	374.1	3.0	377.1	11,992	178.9	336.7	515.6	15,637	553.0	339.7	892.7	27,629
1990	313.6	3.7	317.3	10,188	173.9	180.4	354.3	15,229	487.5	184.1	671.6	25,417
1991	523.7	3.1	526.7	9,404	171.6	159.0	330.6	11,286	695.3	162.1	857.4	20,690
1992	552.2	4.3	556.5	9,820	163.3	128.0	291.3	12,078	715.5	132.3	847.8	21,898
1993	448.3	2.7	451.0	7,342	175.9	94.7	270.6	9,087	624.2	97.3	721.5	16,429
1994	538.0	3.4	541.4	8,091	145.3	174.5	319.8	10,494	683.3	177.9	861.2	18,585
1995	571.3	2.6	573.9	8,300	209.1	285.7	494.8	8,473	780.3	288.3	1,068.6	16,773
1996	682.1	2.1	684.2	7,148	223.2	335.8	559.0	9,559	905.2	337.9	1,243.2	16,707

Year	Blue catch	Red catch	Combined catch	Brown effort	Blue catch	Red catch	Combined catch	Grooved effort	Blue catch	Red catch	Combined catch	Tiger effort
1997	630.8	4.2	635.0	6,360	239.3	971.8	1,211.2	9,037	870.1	976.1	1,846.2	15,397
1998	636.3	3.3	639.6	6,922	403.5	276.3	679.9	10,952	1,039.9	279.6	1,319.5	17,874
1999	379.0	3.2	382.2	4,224	251.6	210.1	461.8	8,935	630.6	213.3	843.9	13,159
2000	344.7	1.5	346.2	3,890	342.8	253.3	596.1	8,764	687.5	254.8	942.3	12,654
2001	230.6	0.7	231.4	2,634	544.6	356.1	900.7	8,041	775.2	356.9	1,132.1	10,675
2002	53.0	0.9	53.9	975	220.0	122.4	342.5	7,889	273.0	123.4	396.4	8,864
2003	47.1	1.2	48.4	653	247.5	121.5	369.0	7,786	294.6	122.8	417.3	8,439
2004	29.9	3.0	32.9	499	228.2	118.5	346.6	7,364	258.1	121.4	379.5	7,863
2005	101.1	3.0	104.1	1,623	110.4	43.8	154.2	6,287	211.5	46.8	258.3	7,910
2006	141.7	1.9	143.6	1,775	142.6	59.7	202.2	5,350	284.3	61.6	345.9	7,125
2007	83.4	1.0	84.4	1,185	70.5	35.2	105.7	3,957	153.9	36.2	190.1	5,142
2008	87.4	0.6	88.1	1,085	66.1	49.5	115.6	3,667	153.5	50.2	203.7	4,752
2009	110.9	2.0	112.8	1,324	124.1	68.1	192.2	3,425	235.0	70.0	305.1	4,749
2010	141.4	4.8	146.2	1,175	168.7	95.8	264.5	3,928	310.1	100.6	410.7	5,103
2011	137.3	1.9	139.2	1,192	119.1	189.6	308.7	3,201	256.4	191.5	447.9	4,393
2012	151.3	1.1	152.3	1,324	125.8	206.7	332.5	4,072	277.0	207.8	484.8	5,396
2013	210.2	3.6	213.8	1,789	128.0	145.2	273.2	4,176	338.1	148.8	486.9	5,965
2014	191.0	2.4	193.4	1,395	179.6	268.7	448.3	3,733	370.6	271.2	641.7	5,128
2015	159.1	4.9	163.9	1,201	176.3	195.9	372.2	4,840	335.4	200.8	536.2	6,041
2016	151.5	2.3	153.8	2,092	123.1	87.8	210.9	3,868	274.7	90.1	364.7	5,960
2017	132.5	3.0	135.6	1,397	81.5	133.0	214.5	3,494	214.0	136.0	350.0	4,891
2018	136.3	2.3	138.6	1,089	139.2	199.9	339.0	4,399	275.4	202.2	477.6	5,488
2019	375.8	3.2	379.0	2,181	125.9	141.3	267.2	3,535	501.7	144.6	646.3	5,716
2020	109.7	2.1	111.8	1,309	117.4	119.6	237.0	4,080	227.2	121.7	348.9	5,389
2021	116.6	2.0	118.7	1,345	142.9	145.6	288.6	3,320	259.6	147.6	407.2	4,665
Average	330.2	6.3	336.5	5,742	221	227	448	8,098	552	233	785	13,840

Table 2. Total annual catch of Endeavour Prawns and the total fishing effort in the NPF from 1970 to 2021. Catch is in metric tonnes. Fishing effort is the total boat-days from two Tiger Prawn fleets and two Banana Prawn fleets.

Year	Blue catch	Red catch	Combined catch	Boat-day
1970	325.9	94.2	420.1	7,813
1971	229.6	137.4	366.9	11,891
1972	246.9	176.1	423.0	11,441
1973	423.7	112.0	535.7	12,092
1974	243.3	166.5	409.8	10,766
1975	296.1	172.8	468.9	11,743
1976	463.6	296.4	760.0	14,459
1977	826.1	368.9	1,195.0	19,220
1978	954.2	278.4	1,232.7	24,177
1979	1,036.5	306.0	1,342.5	25,105
1980	1,583.2	518.4	2,101.6	39,793
1981	1,566.9	789.6	2,356.5	44,526
1982	1,458.5	866.1	2,324.5	42,317
1983	1,076.3	467.5	1,543.8	41,664
1984	1,191.6	575.0	1,766.6	38,542
1985	1,117.5	602.8	1,720.3	33,541
1986	549.6	244.4	793.9	34,087
1987	478.3	263.3	741.7	30,181
1988	451.1	231.4	682.5	32,891
1989	563.5	384.1	947.6	34,572
1990	509.8	229.7	739.5	30,389
1991	708.4	182.8	891.2	27,214
1992	739.7	155.3	894.9	26,840
1993	637.2	115.1	752.3	22,470
1994	692.1	199.7	891.8	23,465
1995	800.7	377.4	1,178.1	21,851
1996	918.2	374.8	1,293.1	22,160
1997	901.5	1,039.9	1,941.4	20,898
1998	1,056.8	290.2	1,347.0	23,428
1999	652.7	232.9	885.6	18,334
2000	698.5	264.9	963.4	16,416
2001	801.3	381.7	1,183.1	16,687
2002	283.6	140.7	424.3	12,997
2003	301.0	135.6	436.6	12,617
2004	261.6	140.2	401.8	11,778
2005	225.6	58.8	284.4	11,422
2006	298.3	64.8	363.2	10,302
2007	155.8	39.1	194.8	7,587
2008	157.3	57.7	215.1	7,778
2009	241.0	86.3	327.3	7,876
2010	315.8	112.3	428.1	8,018
2011	267.5	226.2	493.8	8,142
2012	282.9	212.0	494.9	8,230

Year	Blue catch	Red catch	Combined catch	Boat-day
2013	343.1	163.6	506.7	8,513
2014	377.5	300.1	677.6	8,698
2015	348.0	206.2	554.2	8,723
2016	279.0	94.4	373.3	8,491
2017	218.6	161.3	379.9	8,060
2018	282.7	209.2	491.9	8,580
2019	509.0	147.2	656.2	8,622
2020	233.1	125.4	358.5	7,901
2021	265.8	170.3	436.1	7,676
Average	574.0	264.4	838.3	18,711

Table 3. Catch and catch rate (CPUE) of Red Endeavour Prawns in four stock regions. The number 1 to 4 denotes Endeavour Prawn stock regions in Figure 3.

Year	Catch 1	Catch 2	Catch 3	Catch 4	CPUE 1	CPUE 2	CPUE 3	CPUE 4
1970	5.66	11.12	0.96	76.44	0.016	0.004	0.000	0.027
1971	55.71	39.67	4.46	37.52	0.026	0.014	0.002	0.008
1972	120.31	7.83	3.37	44.56	0.058	0.004	0.001	0.011
1973	49.15	22.88	6.93	33.08	0.039	0.008	0.002	0.007
1974	125.23	31.63	1.68	7.99	0.073	0.018	0.001	0.002
1975	65.91	27.47	2.34	77.08	0.024	0.013	0.001	0.015
1976	211.25	48.07	3.16	33.87	0.058	0.016	0.001	0.006
1977	124.22	104.35	9.52	130.79	0.047	0.019	0.002	0.020
1978	111.96	90.21	5.09	71.17	0.024	0.011	0.001	0.009
1979	151.61	50.18	30.28	73.94	0.034	0.010	0.004	0.011
1980	319.76	93.04	45.79	59.78	0.041	0.009	0.004	0.006
1981	514.09	97.07	41.62	136.78	0.044	0.011	0.004	0.012
1982	503.66	55.2	49.77	257.43	0.051	0.007	0.004	0.021
1983	296.28	59.1	32.96	79.12	0.035	0.007	0.002	0.008
1984	281.77	82.21	87.95	123.11	0.041	0.010	0.007	0.013
1985	198.68	98.44	110.25	195.43	0.031	0.016	0.008	0.026
1986	175.45	27.02	15.89	26	0.019	0.003	0.002	0.004
1987	185.35	49.88	25.56	2.56	0.022	0.008	0.002	0.001
1988	125.15	33.27	28.58	44.43	0.018	0.005	0.002	0.006
1989	145.61	28.04	28.33	182.1	0.022	0.005	0.002	0.018
1990	112.6	21.16	20.3	75.66	0.017	0.004	0.002	0.010
1991	115.49	26.36	19.94	21.01	0.023	0.008	0.002	0.003
1992	45.34	57.51	22.9	29.53	0.009	0.009	0.003	0.004
1993	26.22	33.48	31.41	24	0.006	0.011	0.003	0.005
1994	43.72	93.61	22.26	40.11	0.011	0.020	0.003	0.007
1995	139.09	62.04	29.63	146.62	0.039	0.017	0.005	0.018
1996	55.14	32.48	31.28	255.94	0.016	0.012	0.004	0.028
1997	744.43	56.71	14.31	224.46	0.133	0.018	0.003	0.034
1998	86.26	135	58.13	10.79	0.020	0.030	0.007	0.002
1999	79.18	117.76	30.73	5.26	0.021	0.023	0.004	0.002
2000	34.14	59.35	50.37	121.01	0.013	0.016	0.008	0.034
2001	136.09	125.07	75.65	44.92	0.050	0.038	0.010	0.014
2002	37.54	61.58	32.01	9.59	0.012	0.013	0.012	0.004
2003	33.3	55.78	46.34	0.14	0.011	0.020	0.009	0.000
2004	48.01	53.89	38.28	0.04	0.017	0.016	0.009	0.000
2005	22.37	28.02	8.23	0.15	0.008	0.009	0.002	0.000
2006	10.68	38.51	13.77	1.88	0.006	0.016	0.003	0.001
2007	7	24.04	7.68	0.36	0.005	0.011	0.003	0.000
2008	14.89	16.63	5.15	21.08	0.007	0.012	0.003	0.010
2009	24.88	16.33	17.4	27.69	0.021	0.021	0.005	0.012
2010	15.23	49.41	28.1	19.54	0.011	0.024	0.009	0.013
2011	133.98	26.23	5.84	60.17	0.065	0.021	0.003	0.022
2012	36.44	31.27	11.93	132.37	0.021	0.020	0.005	0.048
2013	63.41	38.72	11.7	49.79	0.037	0.019	0.005	0.022

Year	Catch 1	Catch 2	Catch 3	Catch 4	CPUE 1	CPUE 2	CPUE 3	CPUE 4
2014	112.28	63.55	12.95	111.34	0.052	0.043	0.005	0.045
2015	79.6	86.58	18.37	21.62	0.043	0.034	0.008	0.012
2016	46.48	24.68	13.15	10.05	0.026	0.016	0.004	0.005
2017	74.67	12.55	8.74	65.31	0.033	0.013	0.003	0.040
2018	83.52	34.31	8.06	83.35	0.044	0.023	0.003	0.034
2019	54.75	18.76	14.16	59.51	0.040	0.024	0.004	0.022
2020	90.39	10.41	9.45	15.16	0.035	0.009	0.004	0.009
Average	124.98	50.36	24.56	66.31	0.031	0.015	0.004	0.014

Table 4. Catch and catch rate (CPUE) of Blue Endeavour Prawns in four stock regions. The number 1 to 4 denotes Endeavour Prawn stock regions in Figure 3.

Year	Catch 1	Catch 2	Catch 3	Catch 4	CPUE 1	CPUE 2	CPUE 3	CPUE 4
1970	2.69	134.1	145.29	43.81	0.013	0.054	0.068	0.037
1971	37.4	95.73	72.63	23.81	0.033	0.034	0.035	0.022
1972	48.22	70.3	99.63	28.79	0.019	0.036	0.031	0.021
1973	46.91	172.32	186.64	17.82	0.029	0.061	0.070	0.013
1974	67.05	121.77	38.54	15.9	0.062	0.079	0.052	0.051
1975	95.08	94.29	61.77	45	0.072	0.045	0.045	0.021
1976	183.37	130.69	98.09	51.49	0.090	0.043	0.057	0.035
1977	120.39	283.94	241.1	180.68	0.088	0.053	0.076	0.064
1978	231.04	291.46	182.26	249.47	0.076	0.036	0.051	0.050
1979	195.31	183.49	440.06	217.6	0.070	0.036	0.058	0.063
1980	262.38	333.34	646.59	340.9	0.042	0.034	0.057	0.050
1981	463.99	285.83	481.32	335.77	0.049	0.031	0.044	0.050
1982	264.22	220.16	619.78	354.32	0.048	0.028	0.050	0.034
1983	176.56	177	404.92	317.82	0.023	0.020	0.029	0.038
1984	134.3	210.96	462.25	384.05	0.030	0.025	0.037	0.045
1985	128.37	187.27	600.1	201.73	0.030	0.031	0.048	0.037
1986	108.58	103.95	234.29	102.78	0.019	0.012	0.022	0.023
1987	91.09	86.97	214.24	86.05	0.018	0.015	0.018	0.054
1988	53.88	56.84	211.24	129.15	0.015	0.009	0.018	0.023
1989	45.83	49.26	261.15	207.24	0.015	0.010	0.021	0.027
1990	70.52	64.13	245.51	129.67	0.015	0.012	0.022	0.023
1991	62.45	45.02	335.42	265.54	0.023	0.013	0.031	0.061
1992	47.78	89.6	315.94	286.33	0.011	0.013	0.039	0.059
1993	21.67	54.71	365.02	195.75	0.012	0.017	0.038	0.072
1994	28.42	97.8	328.58	237.27	0.017	0.021	0.038	0.059
1995	47.99	79.9	293.55	379.31	0.037	0.022	0.048	0.060
1996	17.15	63.47	366.27	471.35	0.009	0.023	0.056	0.069
1997	64.86	97.11	335.32	404.2	0.019	0.032	0.061	0.081
1998	49.72	180.27	404.22	422.61	0.022	0.040	0.052	0.106
1999	18.13	161.57	398.08	74.93	0.014	0.032	0.060	0.072
2000	27.18	118.61	361.75	190.98	0.028	0.031	0.064	0.075
2001	104.63	170.65	410.98	115.08	0.080	0.053	0.082	0.078
2002	28.9	100.99	118.71	35.01	0.018	0.022	0.046	0.056
2003	9.91	83.47	187.95	19.68	0.005	0.030	0.041	0.100
2004	12.71	84.92	161.47	2.52	0.013	0.026	0.042	0.080
2005	23.13	52.11	138.88	11.53	0.014	0.017	0.035	0.057
2006	18.69	68.12	206.18	5.34	0.015	0.028	0.050	0.037
2007	4.93	38.41	104.93	7.5	0.009	0.017	0.044	0.051
2008	24.06	25.27	55.24	52.74	0.026	0.018	0.030	0.076
2009	8.44	30.18	127.74	74.69	0.015	0.039	0.042	0.103
2010	7.43	82.97	196.62	28.79	0.011	0.041	0.078	0.092
2011	27.36	51.01	99.95	89.22	0.038	0.045	0.060	0.080
2012	14.87	37.03	101.77	129.21	0.017	0.024	0.053	0.095

Year	Catch 1	Catch 2	Catch 3	Catch 4	CPUE 1	CPUE 2	CPUE 3	CPUE 4
2013	25.73	50.02	135.79	131.54	0.037	0.024	0.063	0.114
2014	41.16	52.96	158.74	124.63	0.058	0.036	0.078	0.123
2015	41	87.65	133.38	85.99	0.052	0.034	0.065	0.101
2016	36	36.5	148.5	57.98	0.036	0.024	0.054	0.071
2017	10.71	20.46	165.96	21.48	0.012	0.021	0.063	0.030
2018	45.73	48.36	140.62	47.94	0.052	0.033	0.057	0.059
2019	23.81	21.89	344.14	119.16	0.031	0.028	0.099	0.139
2020	58.37	20.49	120.89	33.33	0.036	0.017	0.055	0.067
Average	74.12	107.95	249.22	148.73	0.032	0.030	0.050	0.061

Table 5. Biological parameters used to calculate the catch conversion ratio to transform catch in other months to the equivalent catch in August.

	Blue Endeavour (EB)		Red Endeavour (ER)		
	Male	Female	Male	Female	Ref and note
L_{inf}	33.26	43	36.95	51.43	EB from Punt et al. 2010; ER from Zhou et al. 2022
k	2.496	1.924	2.72	2.25	EB from Punt et al. 2010; ER from Zhou et al. 2022
t0	-0.06	-0.02	-0.06	-0.02	EB: assumed to be the same as ER
t_{anchor}	0.08	0.08	0.08	0.08	Zhou et al. 2022
a	0.001392	0.001709	0.004493	0.003434	Venables et al. 2006
b	2.8565	2.7775	2.4495	2.5185	Venables et al. 2006
M	0.045	0.045	0.045	0.045	Assumed to equal Tiger Prawn M

Table 6. Posteriors of classic Bayesian models for Red Endeavour Prawns in the whole NPF. The median values in bold are preferred for the use of comparison between regions, scenarios, or species.

Param	Mean	sd	0.025	0.25	0.5	0.75	0.975
Non-informative, *K*~LN(log(max[C])*8, cv=1000); *r*~LN(log(0.46), cv=1000)							
K	62,567	98,761	2,330	4,480	**11,954**	70,728	332,263
B_{msy}	31,284	49,381	1,165	2,240	**5,977**	35,364	166,131
MSY	3,645	7,251	38	387	**632**	2,827	27,130
r	0.331	0.198	0.002	0.177	**0.335**	0.472	0.719
F_{msy}	0.165	0.099	0.001	0.088	**0.167**	0.236	0.360
q_{com}	3.84E-06	4.18E-06	8.29E-08	3.62E-07	**2.25E-06**	6.41E-06	1.42E-05
q_{surv}	1.76E-05	1.99E-05	3.55E-07	1.61E-06	**9.92E-06**	2.85E-05	6.86E-05
B_{2020}/B_{msy}	1.280	0.367	0.644	1.041	**1.244**	1.476	2.118
F_{2020}/F_{msy}	6.910	1075.965	0.003	0.033	**0.159**	0.289	3.304
C_{2020}/MSY	7.999	1451.450	0.005	0.044	**0.198**	0.324	3.305
Weak-informative: *K*~LN(log(max[C])*8, cv=1); *r*~LN(log(0.46), cv=1)							
K	9,661	7,318	3,023	5,023	**7,302**	11,616	30,037
B_{msy}	4,831	3,659	1,512	2,511	**3,651**	5,808	15,019
MSY	901	719	296	495	**671**	1,026	2,930
r	0.405	0.147	0.143	0.299	**0.399**	0.502	0.708
F_{msy}	0.202	0.073	0.072	0.149	**0.199**	0.251	0.354
q_{com}	4.31E-06	2.72E-06	7.96E-07	2.23E-06	**3.75E-06**	5.75E-06	1.07E-05
q_{surv}	1.98E-05	1.33E-05	3.49E-06	9.91E-06	**1.68E-05**	2.63E-05	5.27E-05
B_{2020}/B_{msy}	1.263	0.299	0.757	1.061	**1.234**	1.431	1.941
F_{2020}/F_{msy}	0.188	0.117	0.035	0.104	**0.169**	0.247	0.464
C_{2020}/MSY	0.221	0.117	0.048	0.137	**0.210**	0.285	0.476
Weak-informative, *K*~LN(log(max[C])*4, cv=1); *r*~LN(log(0.46), cv=1)							
K	5,579	3,285	2,354	3,511	**4,622**	6,502	15,528
B_{msy}	2,790	1,642	1,177	1,756	**2,311**	3,251	7,764
MSY	565	330	236	376	**476**	640	1,475
r	0.436	0.146	0.170	0.332	**0.431**	0.532	0.734
F_{msy}	0.218	0.073	0.085	0.166	**0.216**	0.266	0.367
q_{com}	6.54E-06	3.22E-06	1.52E-06	4.09E-06	**6.12E-06**	8.47E-06	1.40E-05
q_{surv}	3.00E-05	1.60E-05	6.82E-06	1.82E-05	**2.73E-05**	3.87E-05	6.81E-05
B_{2020}/B_{msy}	1.232	0.281	0.758	1.042	**1.204**	1.390	1.869
F_{2020}/F_{msy}	0.235	0.119	0.062	0.154	**0.218**	0.294	0.510
C_{2020}/MSY	0.273	0.118	0.085	0.196	**0.263**	0.333	0.532

Table 7. Weight conversion ratio used to convert catch in months other than August to body weight in August for Blue (EB) and Red (ER) Endeavour Prawns.

	Jan	Feb	March	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
EB	1.51	1.51	1.51	1.51	1.18	1.04	0.99	1.0	1.05	1.13	1.25	1.4
ER	1.36	1.36	1.36	1.36	1.1	0.99	0.97	1.0	1.07	1.18	1.32	1.5

Table 8. Posteriors for Red Endeavour Prawns in the whole NPF. The Bayesian state-space biomass dynamics models were performed using MBE approach where the relative deviance (precision) was set as 0.1% between two updates.

Param	Mean	sd	2.50%	25%	50%	75%	97.50%
Raw catch							
K	4,277.9	361.9	3,615.9	4,025.9	**4,261.6**	4,511.5	5,037.5
B_{msy}	2,138.9	180.9	1,807.9	2,013.0	**2,130.8**	2,255.8	2,518.8
MSY	493.6	49.3	404.6	459.2	**490.9**	525.2	597.4
r	0.462	0.026	0.413	0.444	**0.461**	0.478	0.514
F_{msy}	0.231	0.013	0.207	0.222	**0.230**	0.239	0.257
q_{com}	6.81E-06	1.13E-06	5.01E-06	6.01E-06	**6.68E-06**	7.45E-06	9.41E-06
q_{surv}	3.12E-05	7.75E-06	1.91E-05	2.58E-05	**3.02E-05**	3.55E-05	4.93E-05
B_{2020}/B_{msy}	1.213	0.245	0.772	1.050	**1.198**	1.354	1.755
F_{2020}/F_{msy}	0.221	0.053	0.139	0.185	**0.213**	0.248	0.347
C_{2020}/MSY	0.257	0.026	0.210	0.239	**0.255**	0.273	0.310
Adjusted catch							
K	5,127.7	415.7	4,362.8	4,839.0	**5,110.1**	5,397.3	5,993.4
B_{msy}	2,563.8	207.9	2,181.4	2,419.5	**2,555.0**	2,698.6	2,996.7
MSY	583.9	57.1	480.5	544.1	**581.0**	620.5	704.3
r	0.456	0.026	0.408	0.438	**0.455**	0.472	0.508
F_{msy}	0.228	0.013	0.204	0.219	**0.227**	0.236	0.254
q_{com}	6.83E-06	1.08E-06	5.09E-06	6.07E-06	**6.69E-06**	7.43E-06	9.34E-06
q_{surv}	2.64E-05	6.28E-06	1.64E-05	2.2E-05	**2.56E-05**	2.99E-05	4.1E-05
B_{2020}/B_{msy}	1.119	0.235	0.708	0.964	**1.102**	1.250	1.651
F_{2020}/F_{msy}	0.227	0.055	0.142	0.190	**0.220**	0.256	0.358
C_{2020}/MSY	0.243	0.024	0.200	0.227	**0.242**	0.259	0.293

Table 9. Relative change of adjusted catch (= (Adjusted catch – Raw catch)/Raw catch) for both Red and Blue Endeavour Prawns from 1970 to 2021.

Year	Red	Blue
1970	0.306	0.092
1971	0.221	0.184
1972	0.287	0.143
1973	0.225	0.120
1974	0.230	0.191
1975	0.176	0.167
1976	0.188	0.106
1977	0.253	0.138
1978	0.218	0.157
1979	0.161	0.111
1980	0.202	0.130
1981	0.183	0.123
1982	0.215	0.125
1983	0.265	0.138
1984	0.249	0.144
1985	0.205	0.130
1986	0.141	0.091
1987	0.165	0.092
1988	0.173	0.087
1989	0.187	0.079
1990	0.145	0.088
1991	0.185	0.064
1992	0.187	0.101
1993	0.198	0.082
1994	0.220	0.116
1995	0.235	0.081
1996	0.237	0.100
1997	0.168	0.089
1998	0.212	0.131
1999	0.177	0.095
2000	0.178	0.146
2001	0.170	0.108
2002	0.217	0.185
2003	0.224	0.171
2004	0.213	0.174
2005	0.169	0.075
2006	0.182	0.057
2007	0.219	0.075
2008	0.218	0.062
2009	0.193	0.090
2010	0.216	0.097
2011	0.199	0.071
2012	0.205	0.062
2013	0.157	0.059

Year	Red	Blue
2014	0.176	0.074
2015	0.158	0.086
2016	0.126	0.067
2017	0.162	0.050
2018	0.143	0.064
2019	0.193	0.047
2020	0.123	0.065
2021	0.127	0.089
Mean	0.196	0.105

Table 10. Posteriors of key parameters for Red Endeavour Prawns in four stock regions.

Param	mean	sd	2.50%	25%	**50%**	75%	97.50%
$K[1]$	2,814	658	1,625	2,405	**2,809**	3,118	4,316
$K[2]$	779	269	487	570	**690**	932	1,455
$K[3]$	422	107	248	354	**420**	467	678
$K[4]$	1,140	463	638	941	**1,050**	1,224	2,087
$K.sum$	5,155	960	3,733	4,640	**5,006**	5,463	7,465
$B_{msy}[1]$	1,407	329	813	1,202	**1,405**	1,559	2,158
$B_{msy}[2]$	390	134	243	285	**345**	466	727
$B_{msy}[3]$	211	54	124	177	**210**	234	339
$B_{msy}[4]$	570	231	319	470	**525**	612	1,043
$B_{msy}.sum$	2,578	748	1,499	2,135	**2,485**	2,871	4,267
$MSY[1]$	293	106	119	225	**282**	350	534
$MSY[2]$	74	29	23	57	**69**	87	144
$MSY[3]$	36	17	1	27	**37**	46	70
$MSY[4]$	111	57	14	80	**105**	133	236
$MSY.sum$	515	146	236	429	**509**	596	818
$r[1]$	0.424	0.131	0.155	0.351	**0.421**	0.499	0.697
$r[2]$	0.393	0.122	0.112	0.328	**0.398**	0.465	0.623
$r[3]$	0.347	0.136	0.010	0.280	**0.367**	0.435	0.576
$r[4]$	0.395	0.148	0.053	0.320	**0.398**	0.476	0.692
$r.mean$	0.390	0.102	0.153	0.338	**0.398**	0.454	0.570
$F_{msy}[1]$	0.212	0.066	0.078	0.176	**0.210**	0.250	0.349
$F_{msy}[2]$	0.196	0.061	0.056	0.164	**0.199**	0.233	0.311
$F_{msy}[3]$	0.174	0.068	0.005	0.140	**0.184**	0.218	0.288
$F_{msy}[4]$	0.197	0.074	0.026	0.160	**0.199**	0.238	0.346
$F_{msy}.mean$	0.195	0.067	0.041	0.160	**0.198**	0.234	0.324
$q[1]$	1.52E-05	4.55E-06	8.64E-06	1.21E-05	**1.46E-05**	1.73E-05	2.70E-05
$q[2]$	2.57E-05	9.22E-06	1.09E-05	1.76E-05	**2.55E-05**	3.26E-05	4.35E-05
$q[3]$	1.26E-05	4.81E-06	3.84E-06	9.28E-06	**1.22E-05**	1.55E-05	2.36E-05
$q[4]$	2.00E-05	9.36E-06	5.26E-06	1.45E-05	**1.82E-05**	2.35E-05	4.39E-05
$q.mean$	1.84E-05	6.99E-06	7.15E-06	1.34E-05	**1.76E-05**	2.22E-05	3.45E-05
$B_{2020}/B_{msy}[1]$	1.92	0.42	1.22	1.64	**1.88**	2.15	2.85
$B_{2020}/B_{msy}[2]$	1.12	0.38	0.55	0.85	**1.08**	1.34	1.95
$B_{2020}/B_{msy}[3]$	1.50	0.84	0.64	1.03	**1.31**	1.70	3.74
$B_{2020}/B_{msy}[4]$	1.37	0.90	0.37	0.84	**1.16**	1.60	3.89
$B_{2020}/B_{msy}.mean$	1.48	0.63	0.70	1.09	**1.36**	1.70	3.11
$F_{2020}/F_{msy}[1]$	292.70	32783.62	0.08	0.13	**0.17**	0.22	0.45
$F_{2020}/F_{msy}[2]$	56.30	5122.27	0.06	0.10	**0.14**	0.20	0.48
$F_{2020}/F_{msy}[3]$	1153.93	74878.59	0.08	0.15	**0.21**	0.31	2.60
$F_{2020}/F_{msy}[4]$	10.55	831.39	0.04	0.09	**0.13**	0.19	0.69
$F_{2020}/F_{msy}.mean$	378.37	28403.97	0.07	0.12	**0.16**	0.23	1.05

Table 11. Comparison of the 4-species bio-economic modelling using existing (old) assessment and current (new) assessment developed in this report.

	Existing				Current			
Parameters	Grooved	Brown	Blue	Red	Grooved	Brown	Blue	Red
Steepness	0.394	0.341			0.394	0.341		
C_{2020}	861	1,035	668	277	901	1,030	525	155
Obs C_{2019}	1,177	910	509	147	1,177	910	509	147
C_{msy}	1,693	1,106	733	348	1,690	1,110	742	219
C_{mey}	1,529	1,169	726	260	1,576	1,142	657	166
S_{msy}	0.289	0.229	3,040	1,625	0.291	0.221	9,956	5,642
S_{mey}	0.356	0.239	3,195	1,464	0.343	0.245	10,163	5,548
S_{mey}/S_{msy}	123	104	105	90	118	111	102	98
S_{2019}/S_0	63	67	48	53	63	67	87	102
S_{2019}/S_{msy}	123	130	98	113	122	135	109	122
S_{2019}/S_{mey}	100	125	94	126	103	122	107	124
Mav5y S_{2019}/S_{msy}	131	121	77	104	130	126	94	128
s_{2026}/S_{mey}	100	102	92	114	101	98	89	92
E_{2019}	3,535	2,181			3,535	2,181		
E_{2020}	3,060	3,372			3,298	3,286		
E_{msy}	7,408	2,420			7,276	2,552		
E_{mey}	4,744	3,096			5,249	2,777		
E_{mey}/E_{msy}	64	128			72	109		
E_{2019}/E_{msy}	48	90			49	86		
E_{2019}/E_{mey}	74	70			67	78		
Standard E_{2019}/E_{msy}	47	88			48	84		
Standard E_{2019}/E_{mey}	74	69			66	77		
Standard E_{2019}	6,513	3,994			6,513	3,994		
Standard E_{2020}	5,715	6,298			6,159	6,136		
Profit_{2019}	2.8				2.8			
TotNetPrjProfit	332,126				304,376			

Table 12. Posteriors for Blue Endeavour Prawns in the whole NPF. The Bayesian state-space biomass dynamics models were performed using MBE approach where the relative deviance (precision) was set as 0.1% between two updates.

Param	Mean	sd	0.025	0.25	**0.5**	0.75	0.975
Raw catch							
K	9,416.9	1,159.7	7,408.7	8,597.5	**9,326.9**	10,139.4	11,954.3
B_{msy}	4,708.4	579.9	3,704.3	4,298.7	**4,663.4**	5,069.7	5,977.1
MSY	967.4	153.3	710.5	858.8	**952.7**	1,059.8	1,309.7
r	0.412	0.047	0.326	0.378	**0.409**	0.442	0.512
F_{msy}	0.206	0.024	0.163	0.189	**0.205**	0.221	0.256
q_{com}	7.30E-06	1.38E-06	4.97E-06	6.31E-06	**7.17E-06**	8.14E-06	1.03E-05
q_{surv}	9.11E-04	1.82E-04	6.09E-04	7.82E-04	**8.92E-04**	1.02E-03	1.32E-03
B_{2020}/B_{msy}	1.132	0.190	0.788	1.001	**1.122**	1.252	1.536
F_{2020}/F_{msy}	0.225	0.055	0.137	0.186	**0.218**	0.256	0.354
C_{2020}/MSY	0.247	0.038	0.178	0.220	**0.245**	0.271	0.328
Adjusted catch							
K	10,857.6	834.5	9,323.4	10,277.7	**10,822.5**	11,396.1	12,597.8
B_{msy}	5,428.8	417.2	4,661.7	5,138.9	**5,411.2**	5,698.1	6,298.9
MSY	1,002.9	107.2	811.2	928.0	**996.3**	1,070.8	1,232.4
r	0.370	0.029	0.316	0.350	**0.369**	0.388	0.430
F_{msy}	0.185	0.015	0.158	0.175	**0.184**	0.194	0.215
q_{com}	7.15E-06	1.18E-06	5.22E-06	6.32E-06	**7.02E-06**	7.82E-06	9.85E-06
q_{surv}	8.23E-04	1.45E-04	5.90E-04	7.21E-04	**8.06E-04**	9.05E-04	1.16E-03
B_{2020}/B_{msy}	1.071	0.187	0.731	0.942	**1.062**	1.190	1.466
F_{2020}/F_{msy}	0.241	0.052	0.158	0.204	**0.234**	0.271	0.363
C_{2020}/MSY	0.250	0.027	0.201	0.232	**0.249**	0.267	0.306

Table 13. Posteriors of key parameters for Blue Endeavour Prawns in four stock regions.

Param	mean	sd	2.50%	25%	**50%**	75%	97.50%
$K[1]$	1,798	332	1,229	1,596	**1,790**	1,939	2,569
$K[2]$	1,781	595	1,184	1,373	**1,579**	2,008	3,433
$K[3]$	2,736	446	2,107	2,449	**2,632**	2,927	3,870
$K[4]$	2,489	711	1,759	1,995	**2,306**	2,749	4,560
$K.sum$	8,804	1,422	7,306	7,802	**8,348**	9,363	12,671
$B_{msy}[1]$	899	166	615	798	**895**	970	1,285
$B_{msy}[2]$	891	297	592	687	**789**	1,004	1,717
$B_{msy}[3]$	1,368	223	1,053	1,225	**1,316**	1,464	1,935
$B_{msy}[4]$	1,245	355	880	998	**1,153**	1,375	2,280
$B_{msy}.sum$	4,402	1,042	3,140	3,707	**4,154**	4,812	7,216
$MSY[1]$	215	104	76	154	**199**	252	453
$MSY[2]$	126	37	59	102	**125**	148	207
$MSY[3]$	373	69	251	326	**369**	415	521
$MSY[4]$	424	192	189	291	**377**	506	938
$MSY.sum$	1,139	252	780	970	**1,097**	1,254	1,756
$r[1]$	0.483	0.238	0.175	0.358	**0.446**	0.554	0.998
$r[2]$	0.304	0.105	0.109	0.227	**0.302**	0.378	0.512
$r[3]$	0.555	0.112	0.344	0.477	**0.553**	0.630	0.777
$r[4]$	0.705	0.320	0.318	0.483	**0.623**	0.832	1.605
$r.mean$	0.512	0.122	0.334	0.435	**0.495**	0.564	0.801
$F_{msy}[1]$	0.242	0.119	0.087	0.179	**0.223**	0.277	0.499
$F_{msy}[2]$	0.152	0.053	0.054	0.113	**0.151**	0.189	0.256
$F_{msy}[3]$	0.277	0.056	0.172	0.239	**0.277**	0.315	0.388
$F_{msy}[4]$	0.352	0.160	0.159	0.242	**0.311**	0.416	0.802
$F_{msy}.mean$	0.256	0.097	0.118	0.193	**0.241**	0.299	0.486
$q[1]$	2.56E-05	5.8E-06	1.58E-05	2.15E-05	**2.51E-05**	2.91E-05	3.821E-05
$q[2]$	4.07E-05	1.22E-05	2.23E-05	3.09E-05	**3.88E-05**	4.84E-05	6.855E-05
$q[3]$	2.51E-05	4.23E-06	1.67E-05	2.24E-05	**2.54E-05**	2.81E-05	3.292E-05
$q[4]$	3.29E-05	7.92E-06	1.63E-05	2.78E-05	**3.26E-05**	3.85E-05	4.839E-05
$q.mean$	3.11E-05	7.55E-06	1.78E-05	2.56E-05	**3.05E-05**	3.60E-05	4.70E-05
$B_{2020}/B_{msy}[1]$	1.764	0.574	0.860	1.359	**1.698**	2.080	3.098
$B_{2020}/B_{msy}[2]$	0.366	0.101	0.214	0.296	**0.350**	0.418	0.608
$B_{2020}/B_{msy}[3]$	1.478	0.195	1.120	1.351	**1.467**	1.595	1.900
$B_{2020}/B_{msy}[4]$	1.913	0.295	1.383	1.731	**1.893**	2.062	2.587
$B_{2020}/B_{msy}.mean$	1.380	0.291	0.894	1.184	**1.352**	1.539	2.048
$F_{2020}/F_{msy}[1]$	0.212	0.211	0.061	0.127	**0.176**	0.249	0.560
$F_{2020}/F_{msy}[2]$	0.523	1.088	0.259	0.390	**0.479**	0.585	0.960
$F_{2020}/F_{msy}[3]$	0.231	0.055	0.144	0.193	**0.224**	0.261	0.360
$F_{2020}/F_{msy}[4]$	0.050	0.022	0.018	0.034	**0.047**	0.062	0.096
$F_{2020}/F_{msy}.mean$	0.254	0.344	0.121	0.186	**0.231**	0.289	0.494

Table 14. Comparison of the 3-species bio-economic modelling using existing assessment and current assessment developed in this report.

	Existing			Current		
Parameters	Grooved	Brown	Blue	Grooved	Brown	Blue
Steepness	0.394	0.341		0.394	0.341	
C_{2020}	816	1,022	705	875	927	538
Obs C_{2019}	1,178	908	509	1,178	908	509
C_{msy}	1,687	1,113	808	1,690	1,110	763
C_{mey}	1,526	1,170	747	1,553	1,161	670
S_{msy}	0.294	0.214	3,480	0.291	0.221	9,840
S_{mey}	0.357	0.239	3,489	0.35	0.238	10,148
S_{mey}/S_{msy}	122	112	100	120	108	103
S_{2019}/S_0	63	67	48	63	67	87
S_{2019}/S_{msy}	121	139	86	122	135	111
S_{2019}/S_{mey}	99	125	86	101	125	107
Mav5y S_{2019}/S_{msy}	129	130	68	130	125	96
s_{2026}/S_{mey}	100	101	85	100	102	88
E_{2019}	3,535	2,181		3,535	2,181	
E_{2020}	2,816	3,390		3,187	2,910	
E_{msy}	7,163	2,665		7,286	2,542	
E_{mey}	4,723	3,099		4,982	2,998	
E_{mey}/E_{msy}	66	116		68	118	
E_{2019}/E_{msy}	49	82		48	86	
E_{2019}/E_{mey}	75	70		71	73	
Standard E_{2019}/E_{msy}	49	80		48	84	
Standard E_{2019}/E_{mey}	74	69		70	71	
Standard E_{2019}	6,513	3,994		6,513	3,994	
Standard E_{2020}	5,258	6,331		5,952	5,434	
Profit_{2019}	6.7			6.7		
TotNetPrjProfit	300,210			288,496		

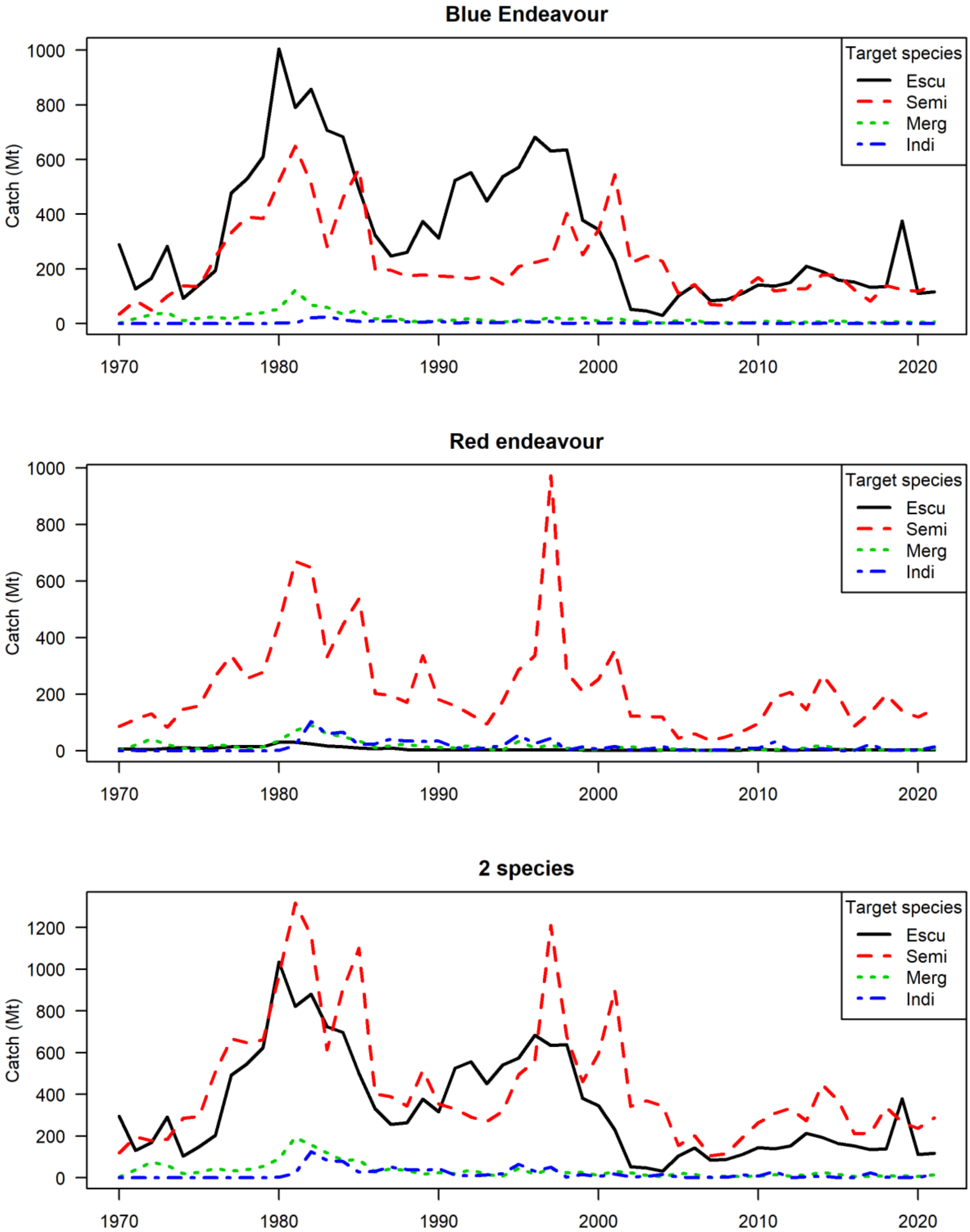

Figure 1. Catch history of Blue Endeavour, Red Endeavour, and two species combined over the NPF history from 1970 to 2021. The target species is identified by their dominant catch in the multi-species mixed fishery.

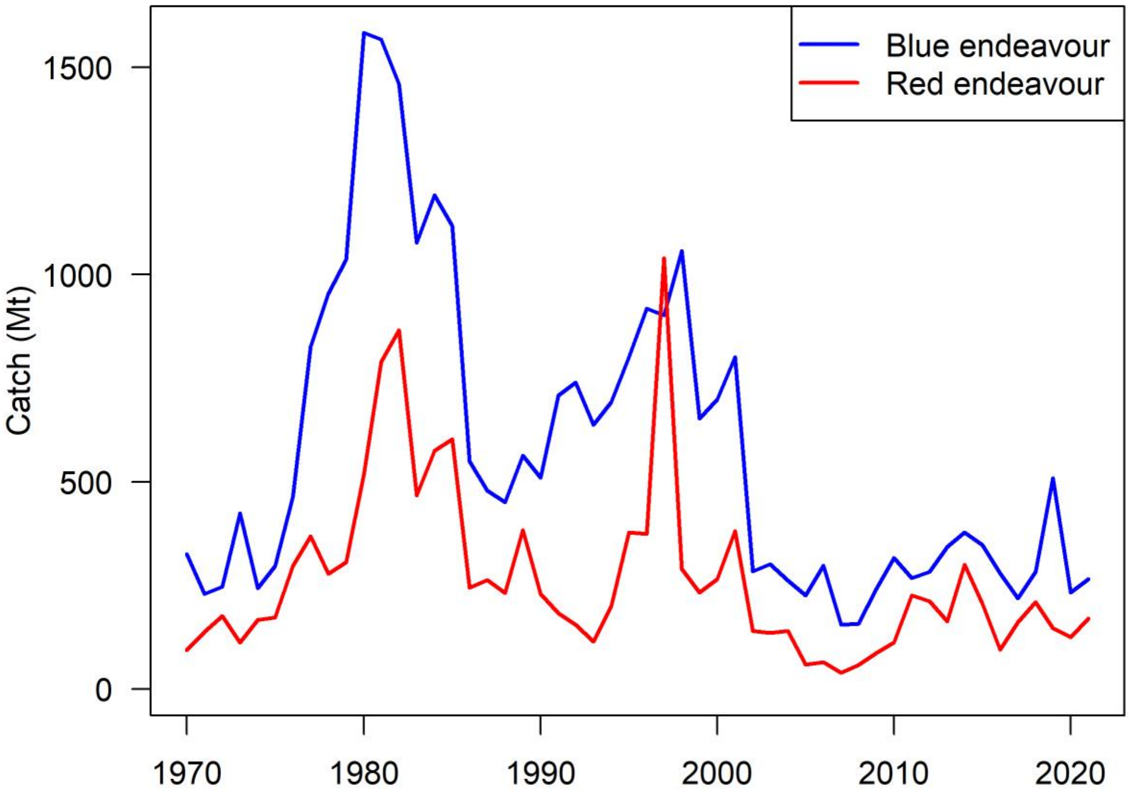

Figure 2. Total annual catch of Blue and Red Endeavour Prawns by all prawn fleets from 1970 to 2021 in the NPF.

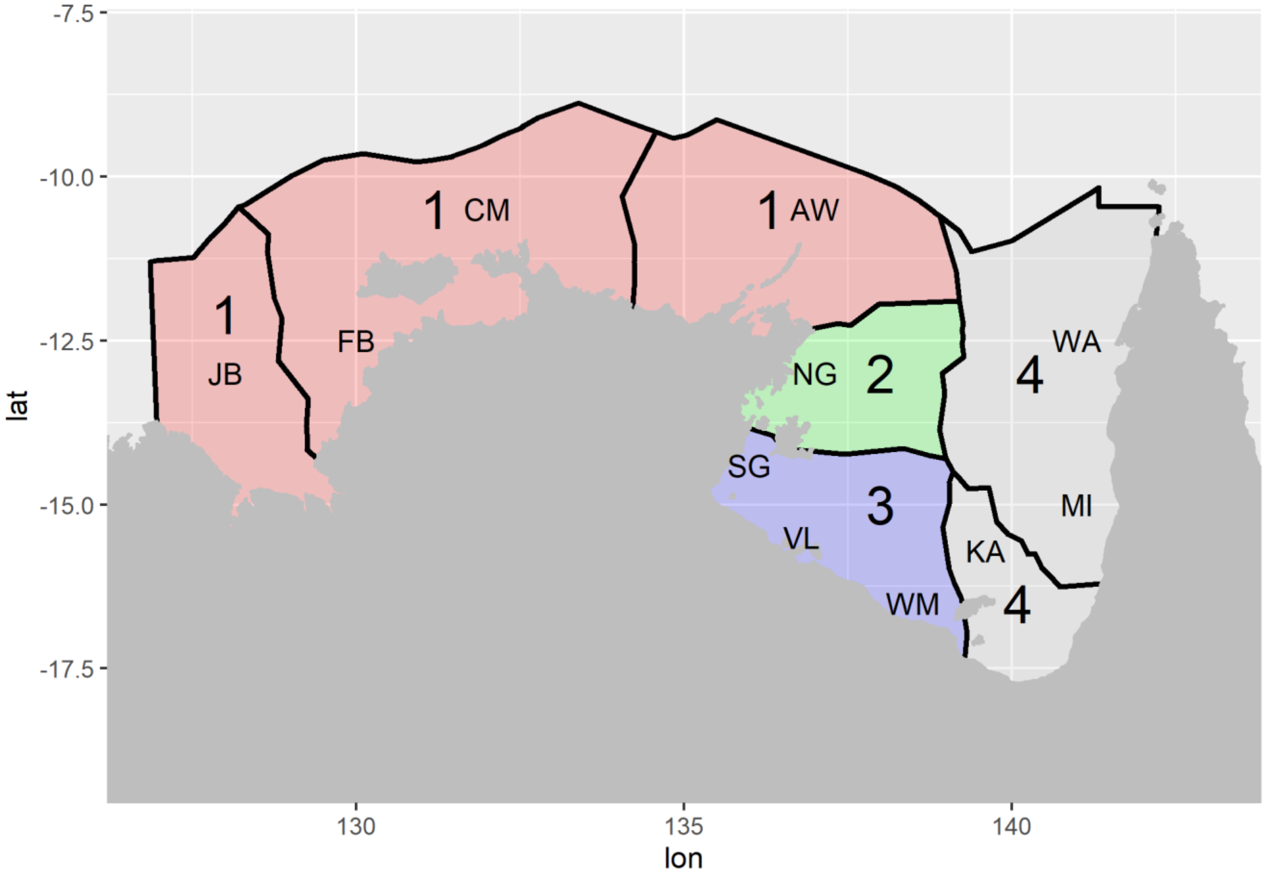

Figure 3. Four Endeavour Prawn Stock Regions (identified by colour) based on seven Tiger Prawn Stock Regions in the NPF. Region 1: Outside GoC, which is made up of 3 Tiger Stock Regions; Region 2: Groote; Region 3: Vanderlins; and Region 4: Weipa, which is made up of 2 Tiger Stock Regions.

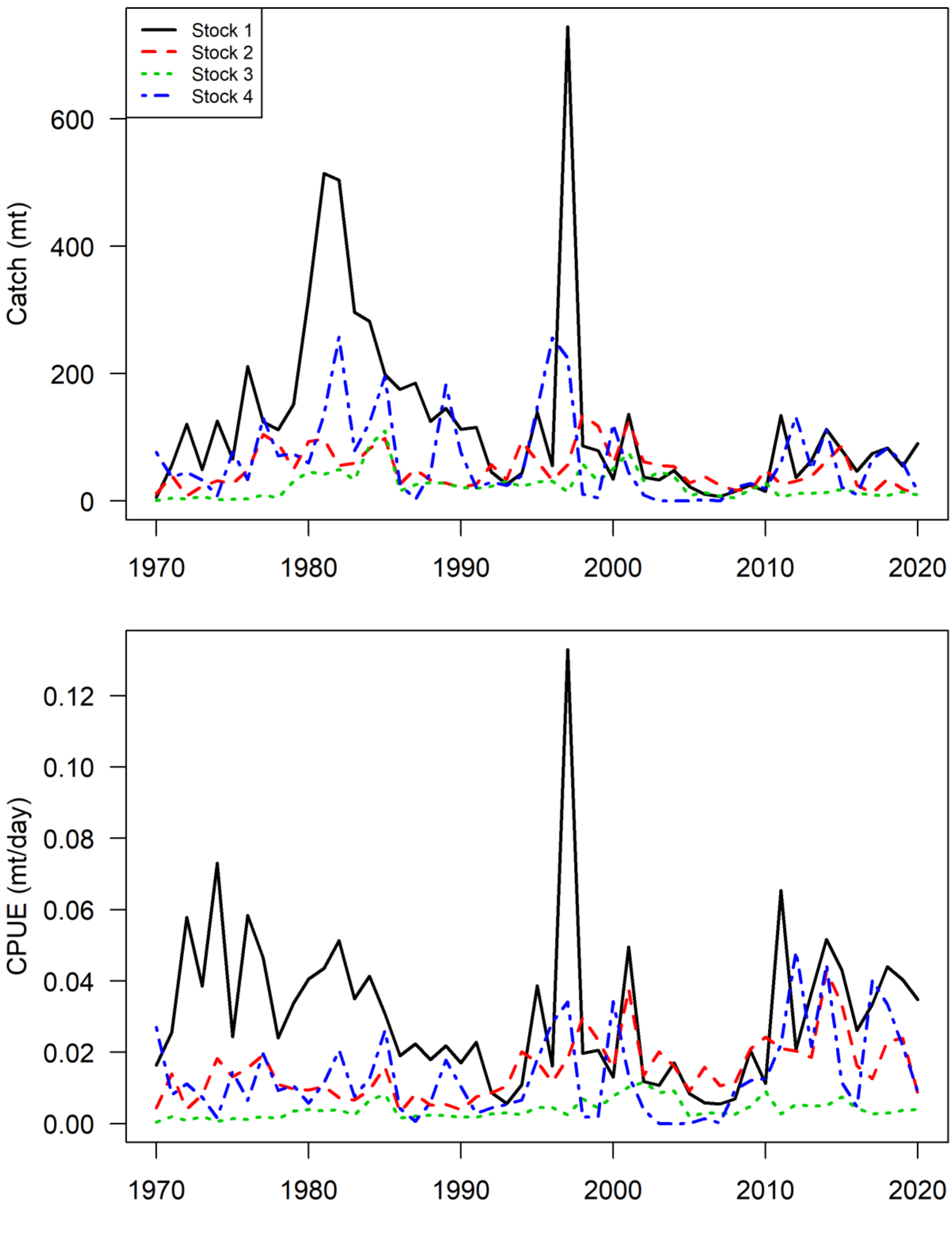

Figure 4. Catch and CPUE of Red Endeavour Prawns in four stock regions from 1970 to 2020.

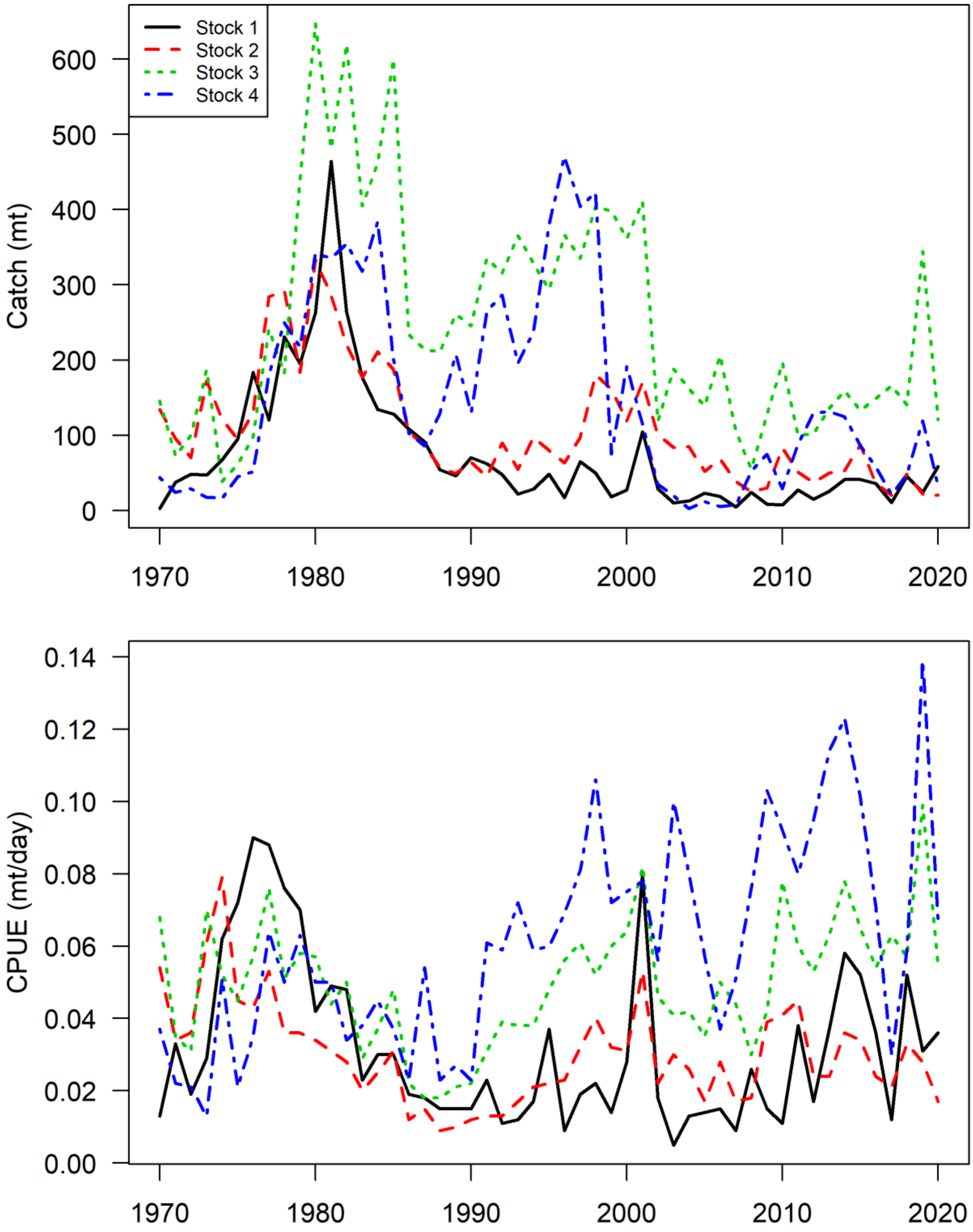

Figure 5. Catch and CPUE of Blue Endeavour Prawns in four stock regions from 1970 to 2020.

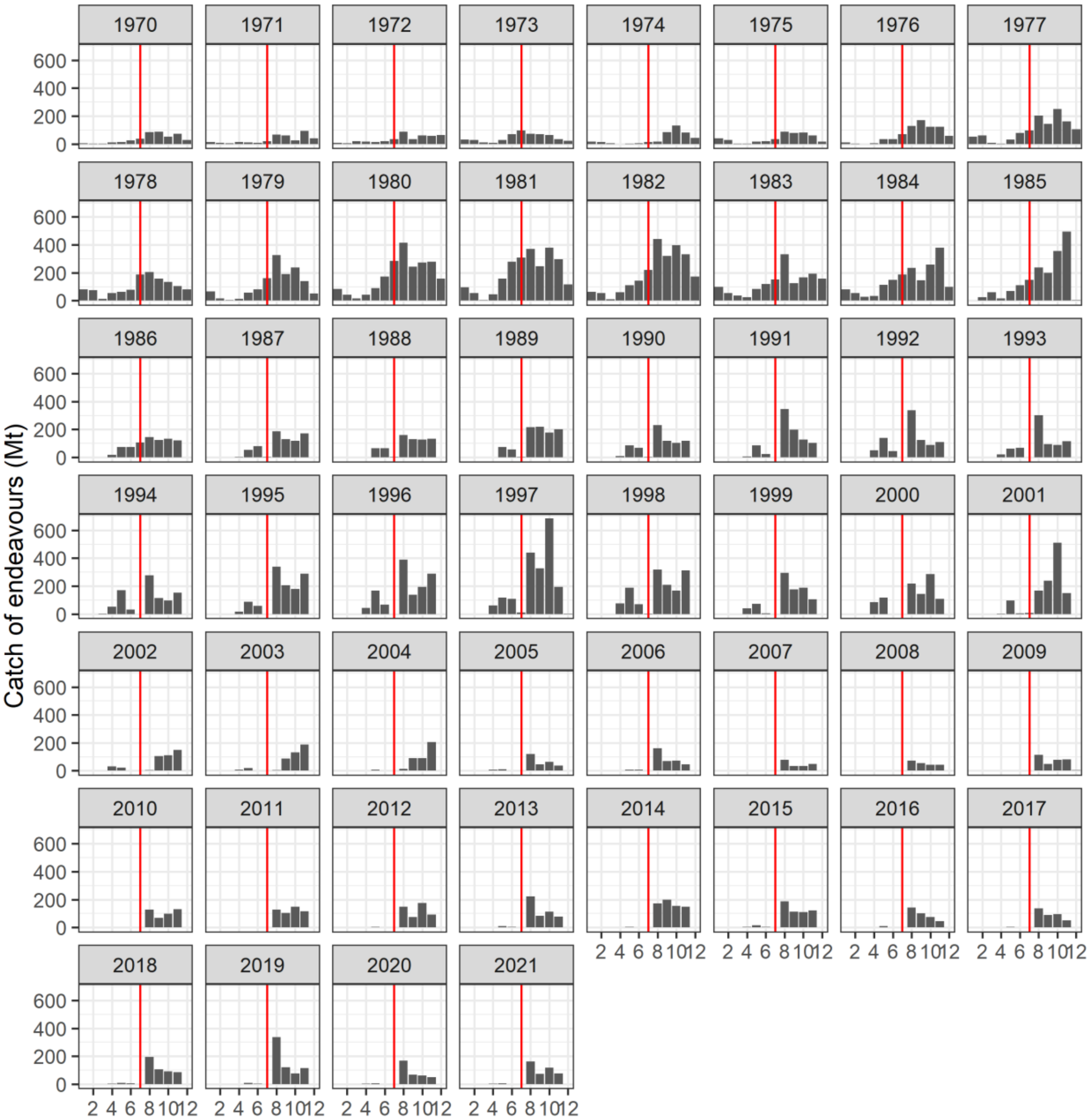

Figure 6. Monthly catch of combined two species of Endeavour Prawns in the NPF from 1970 to 2021. The red vertical line is July, which separate a year into two seasons, the first and the second fishing seasons.

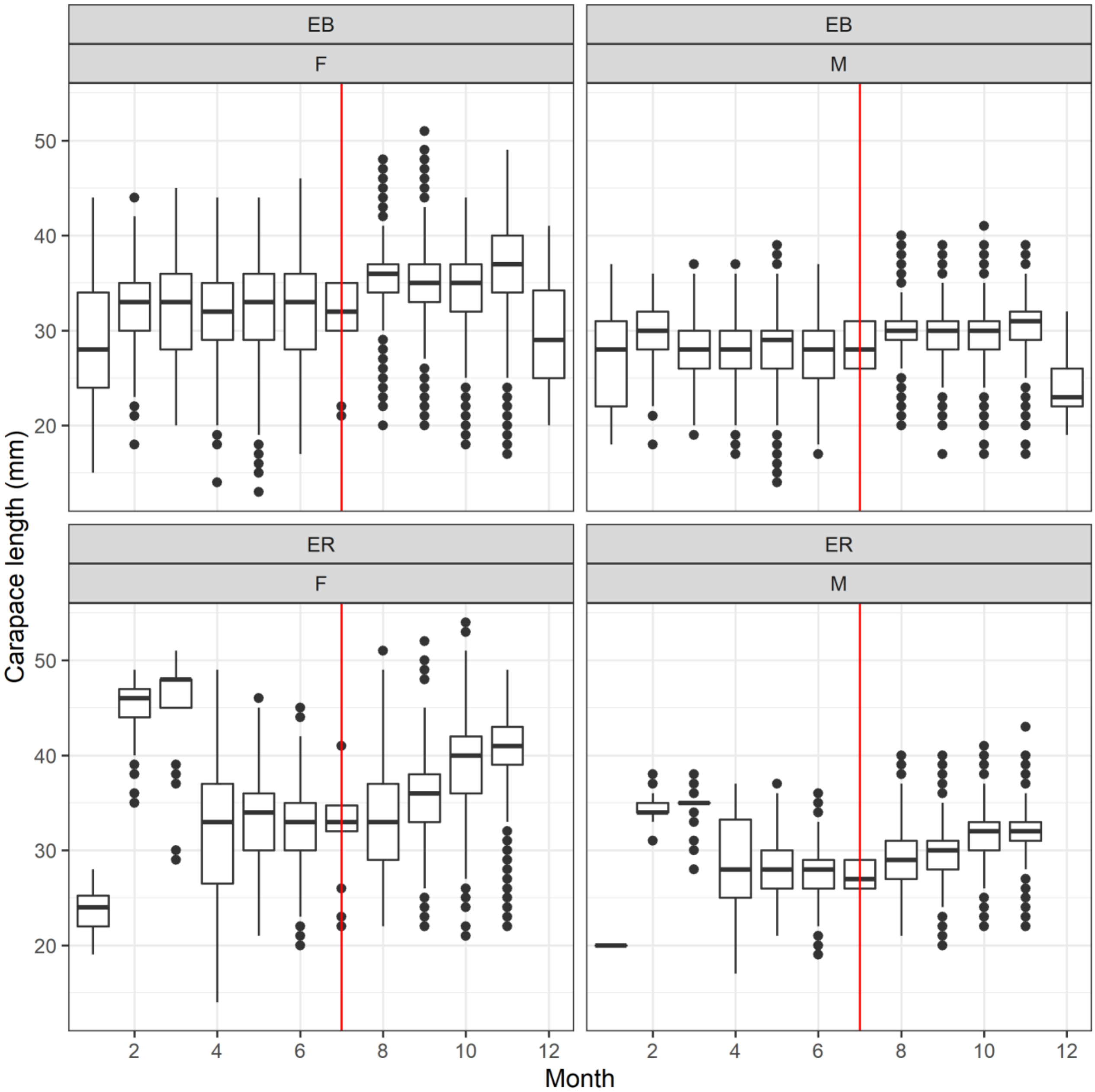

Figure 7. Monthly carapace length of Endeavour Prawns from historical commercial catch samples. EB = Blue Endeavour, ER = Red Endeavour, F = female, M = male. The red vertical line is July, which separate a year into two seasons, the first and the second fishing seasons.

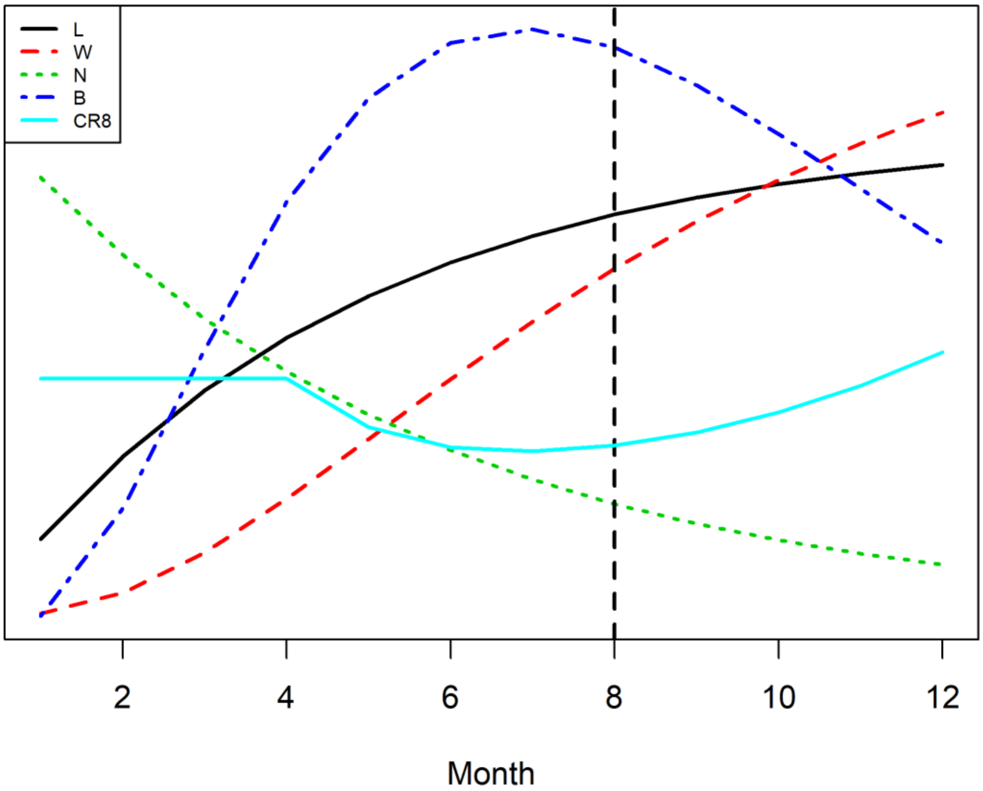

Figure 8. Illustration of Endeavour Prawn year-class development. L = body length, W = body weight, N = abundance, B = cohort biomass, CR8 = catch conversion ratio relative to catch in August. For example, if prawns were harvest in April when the cohort biomass is relatively low the impact on the population dynamics would be greater than when the same biomass of prawns was harvested in August.

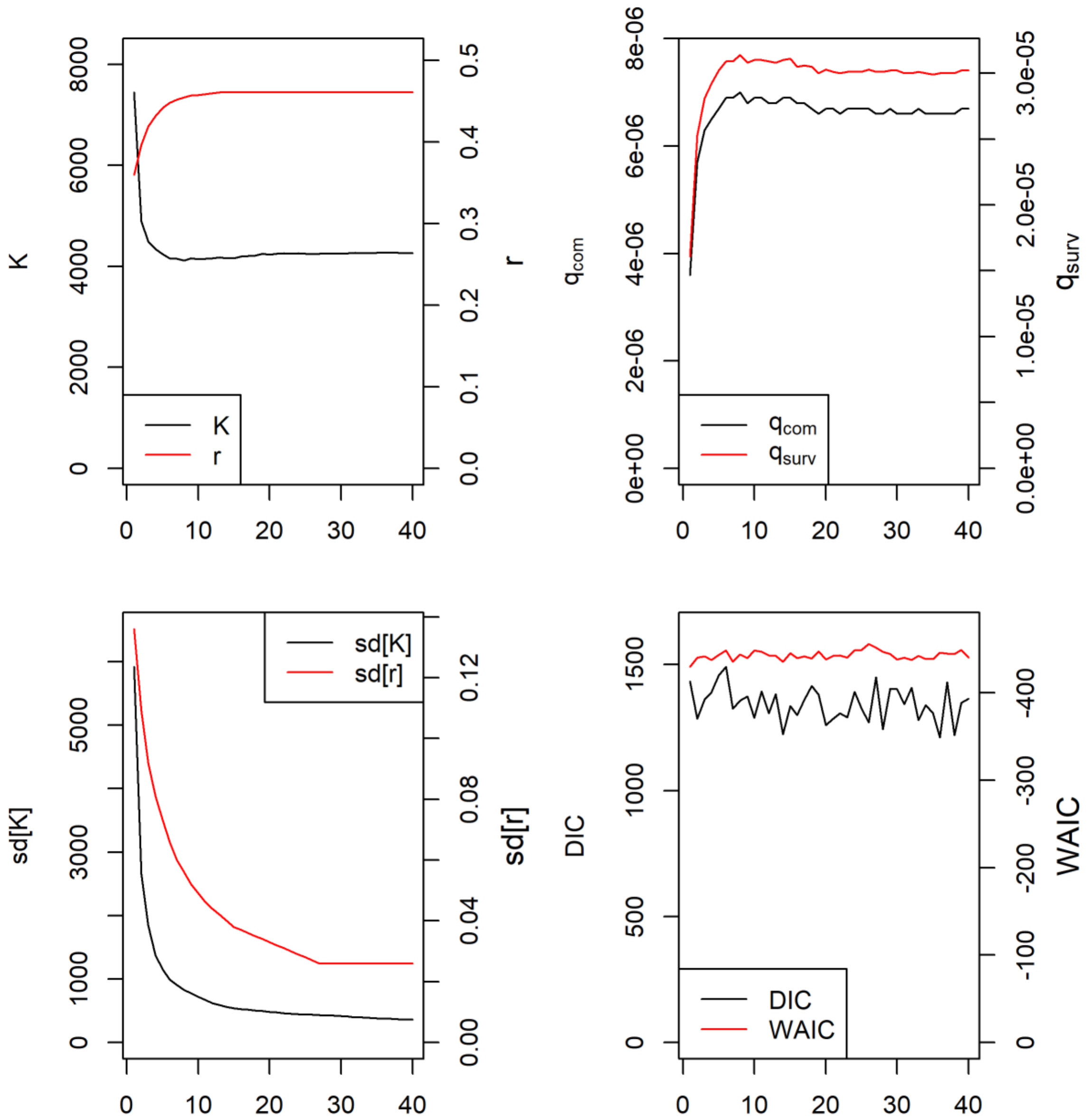

Figure 9. Example of repeating Bayesian production model for Red Endeavour Prawns with 40 runs. Parameter *K* was search using MBE. The curves are the median posteriors for each parameter.

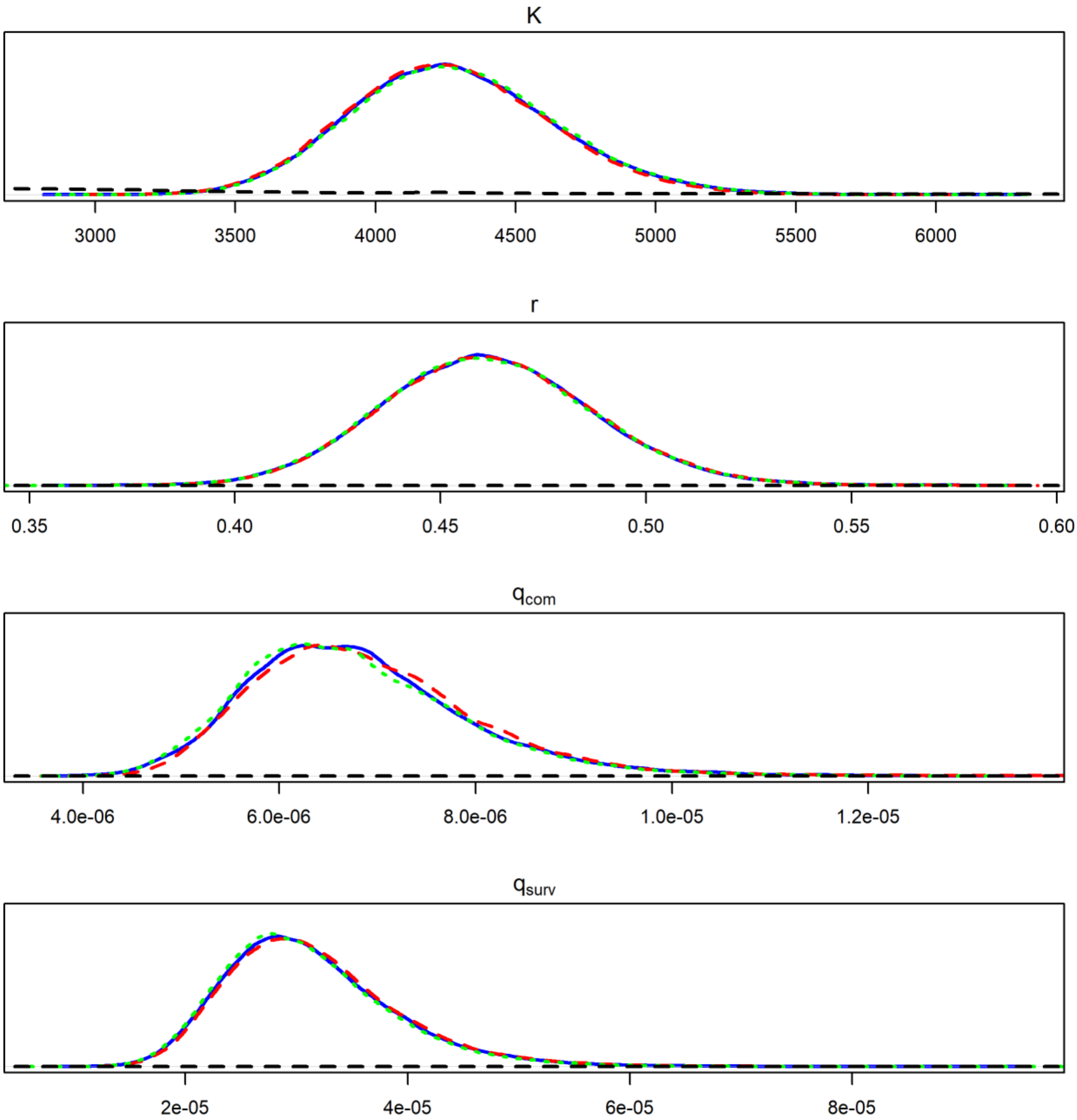

Figure 10. Posterior density distributions for key parameters (*K*, *r*, q_{com}, and q_{surv}) from the Bayesian state-space biomass dynamics model of <u>Red Endeavour Prawns</u>. The three coloured lines (red, green, and blue) represent three MCMC chains and the dashed black lines are priors. The model assumes one single stock fished by Tiger Prawn fleet and uses raw catch in the logbooks.

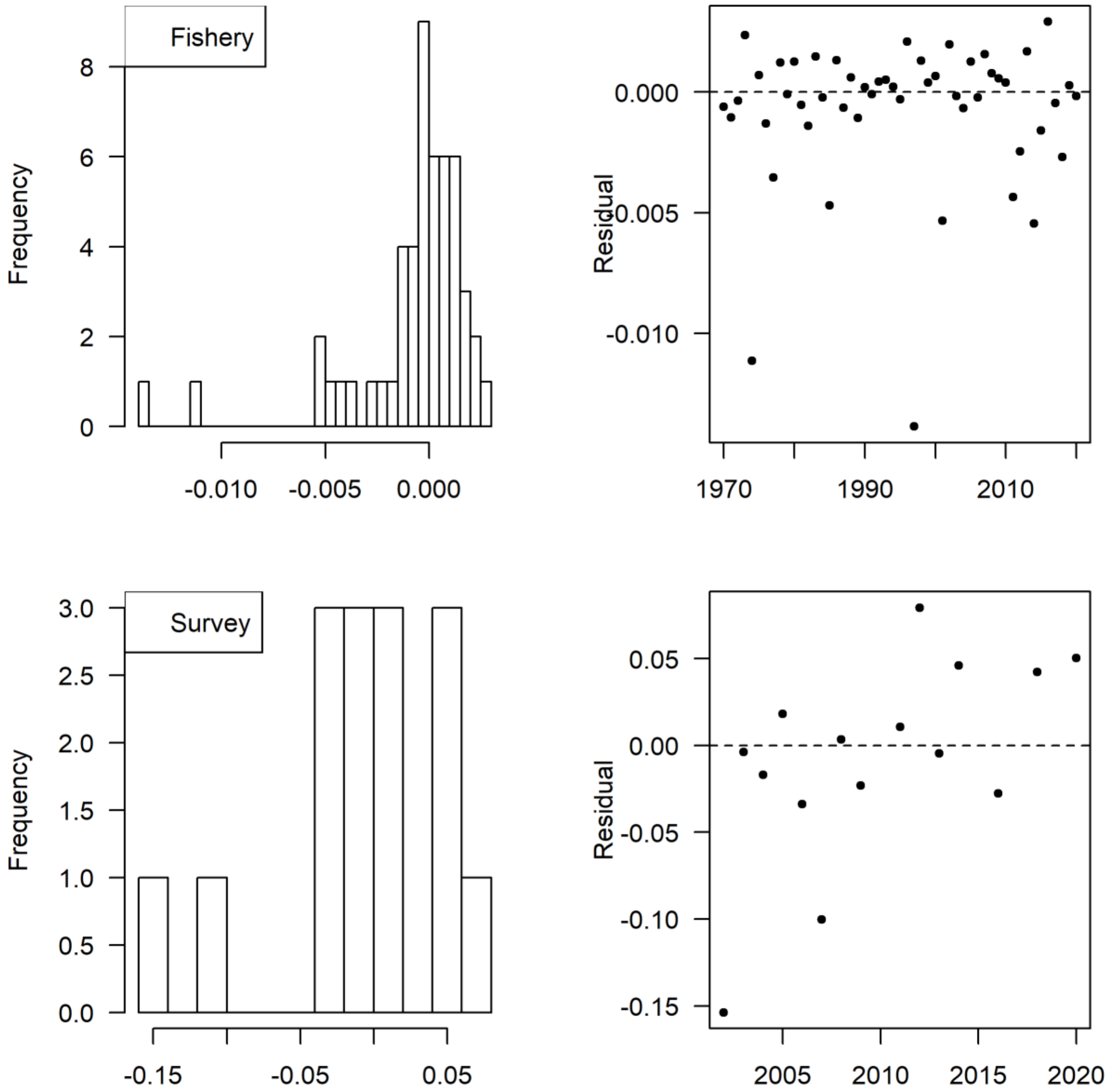

Figure 11. Residuals of Bayesian production model fitted to annual commercial standardized CPUE and spawning survey index of Red Endeavour Prawns. The whole NPF is treated as one single stock and the raw catch from logbooks was used.

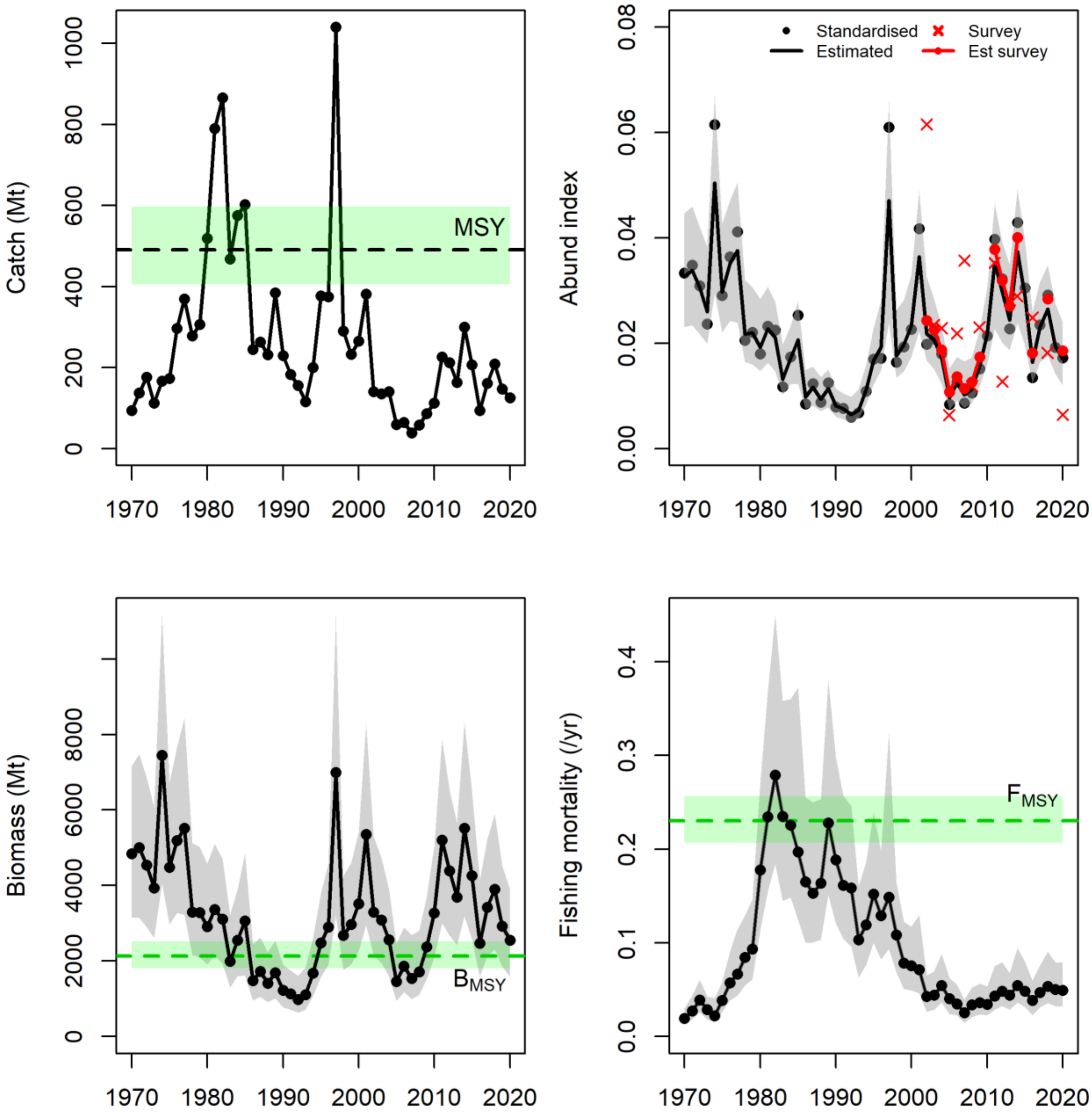

Figure 12. Result of Red Endeavour Prawns, assuming one single stock fished by Tiger Prawn fleet. The y-axis labels in each panel denote the posteriors of the Bayesian state-space biomass dynamics model. The model uses raw catch data and CPUE is relative to 1995 abundance index. The error bars and the grey or green bands are 95% credible intervals. Note the survey index has a second y-axis (scale not shown) so the plot indicates model fitting and relative pattern only but not absolute scale.

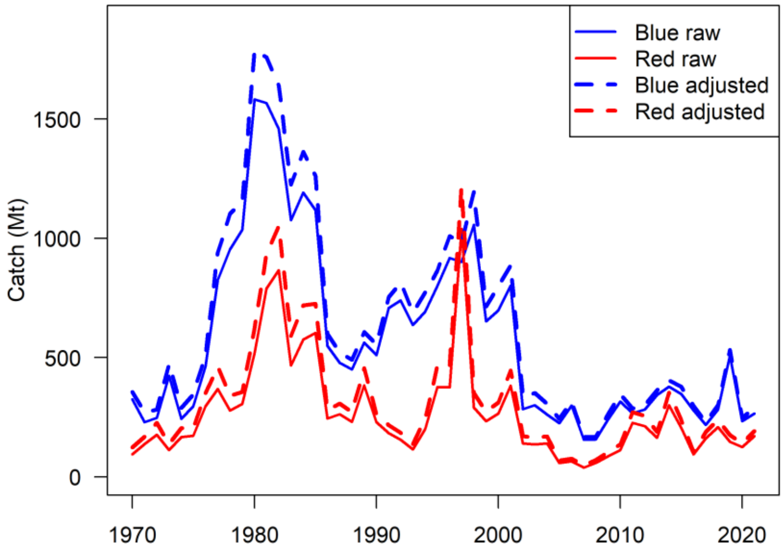

Figure 13. Annual catch of the two species of Endeavour Prawns. Raw: from original logbooks; Adjusted: catch in months other than August are converted to equivalent amount if these prawns were harvested in August.

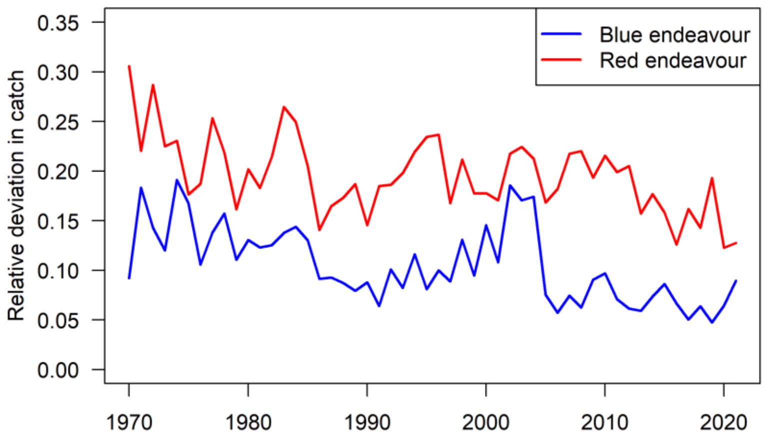

Figure 14. Relative deviation of adjusted catch relative to August from raw catch in the original logbooks.

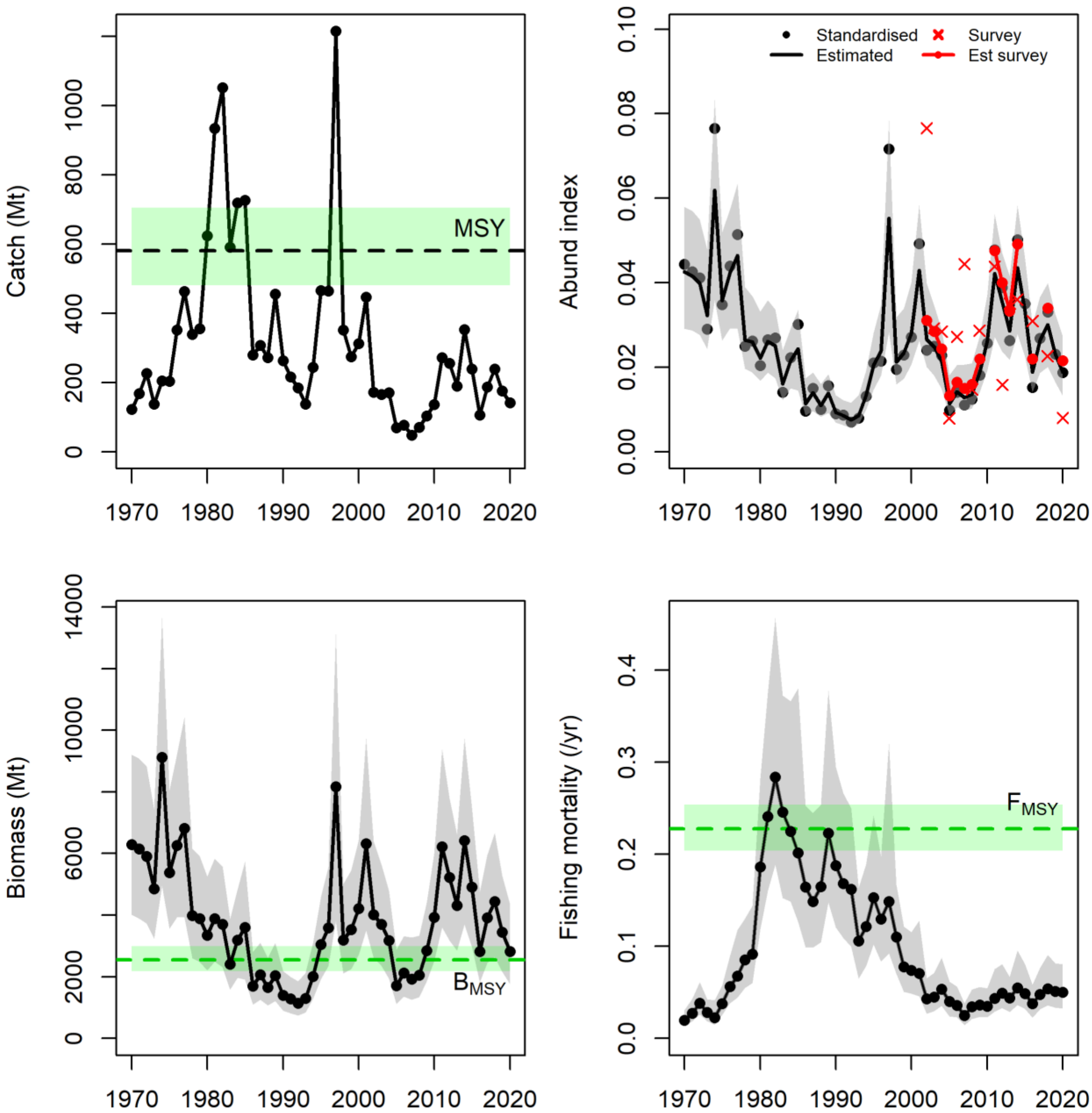

Figure 15. Result of <u>Red Endeavour Prawns</u> from the single stock model using adjusted catch. The y-axis labels in each panel denote the posteriors of the Bayesian state-space biomass dynamics model. The model assumes one single stock fished by Tiger Prawn fleet and the time series of CPUE is relative to 1995 abundance index. The error bars and the grey or green bands are 95% credible intervals. Note the survey index has a second y-axis (scale not shown) so the plot indicates model fitting and relative pattern only but not absolute scale.

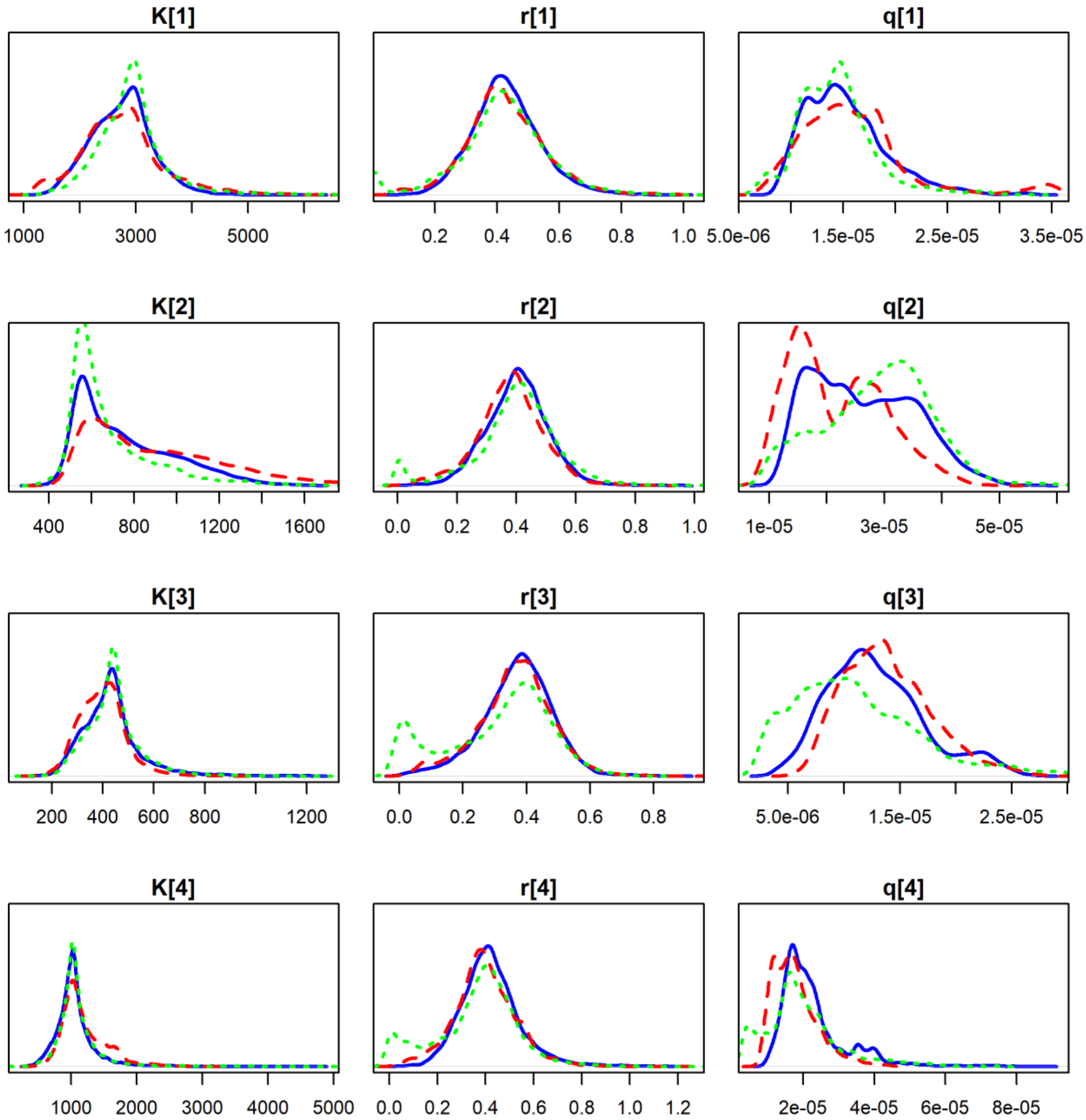

Figure 16. Posterior density distributions for key parameters (*K*, *r*, and *q*) from the Bayesian state-space biomass dynamics model of Red Endeavour Prawns. The three coloured lines represent three MCMC chains. The model assumes four independent stocks fished by Tiger Prawn fleet and uses raw catch in the logbooks.

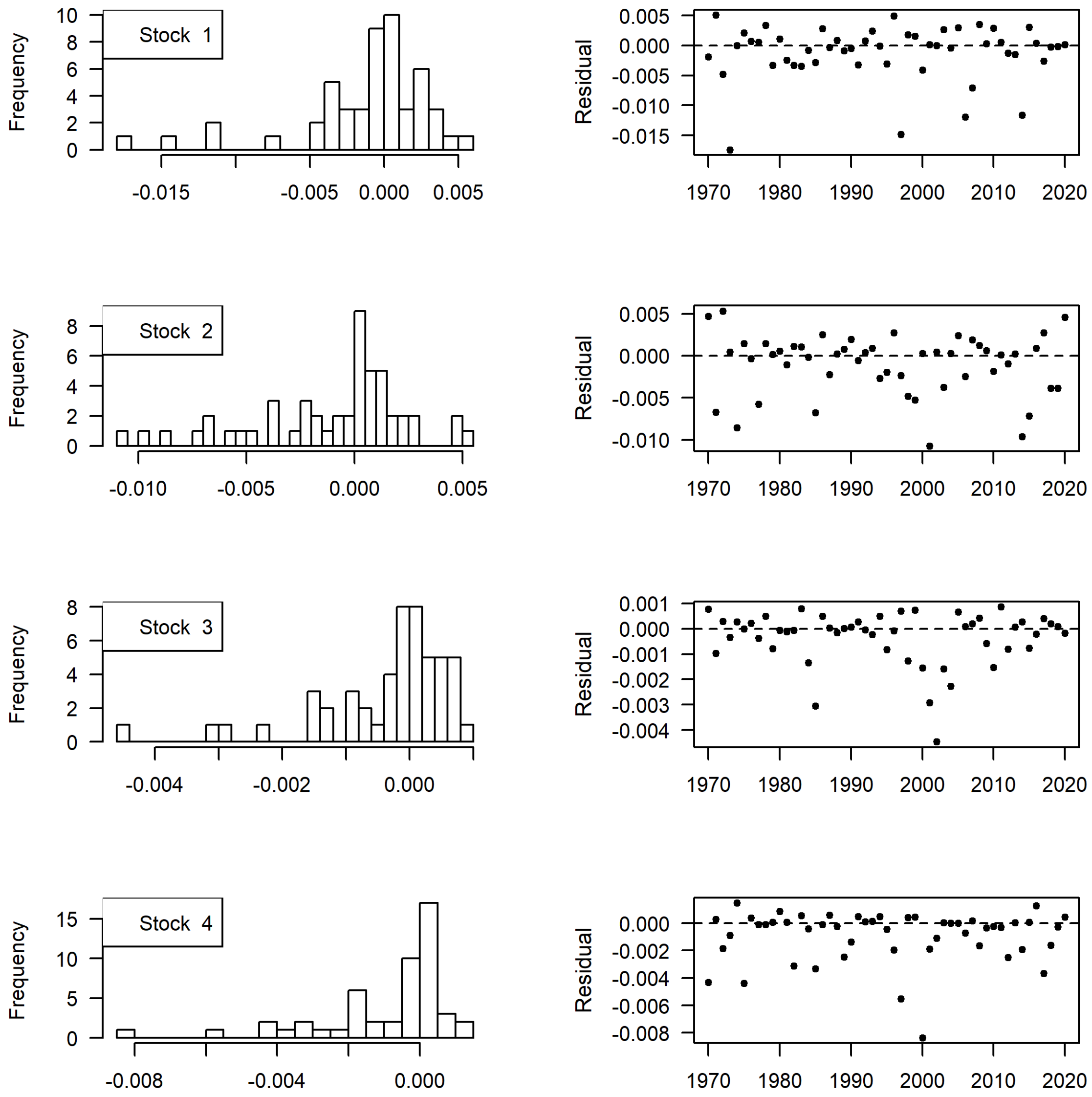

Figure 17. Residuals of Bayesian production model fitted to annual commercial standardized CPUE of Red Endeavour Prawns. Four independent stocks are assumed in the NPF and the raw catch from logbooks was used.

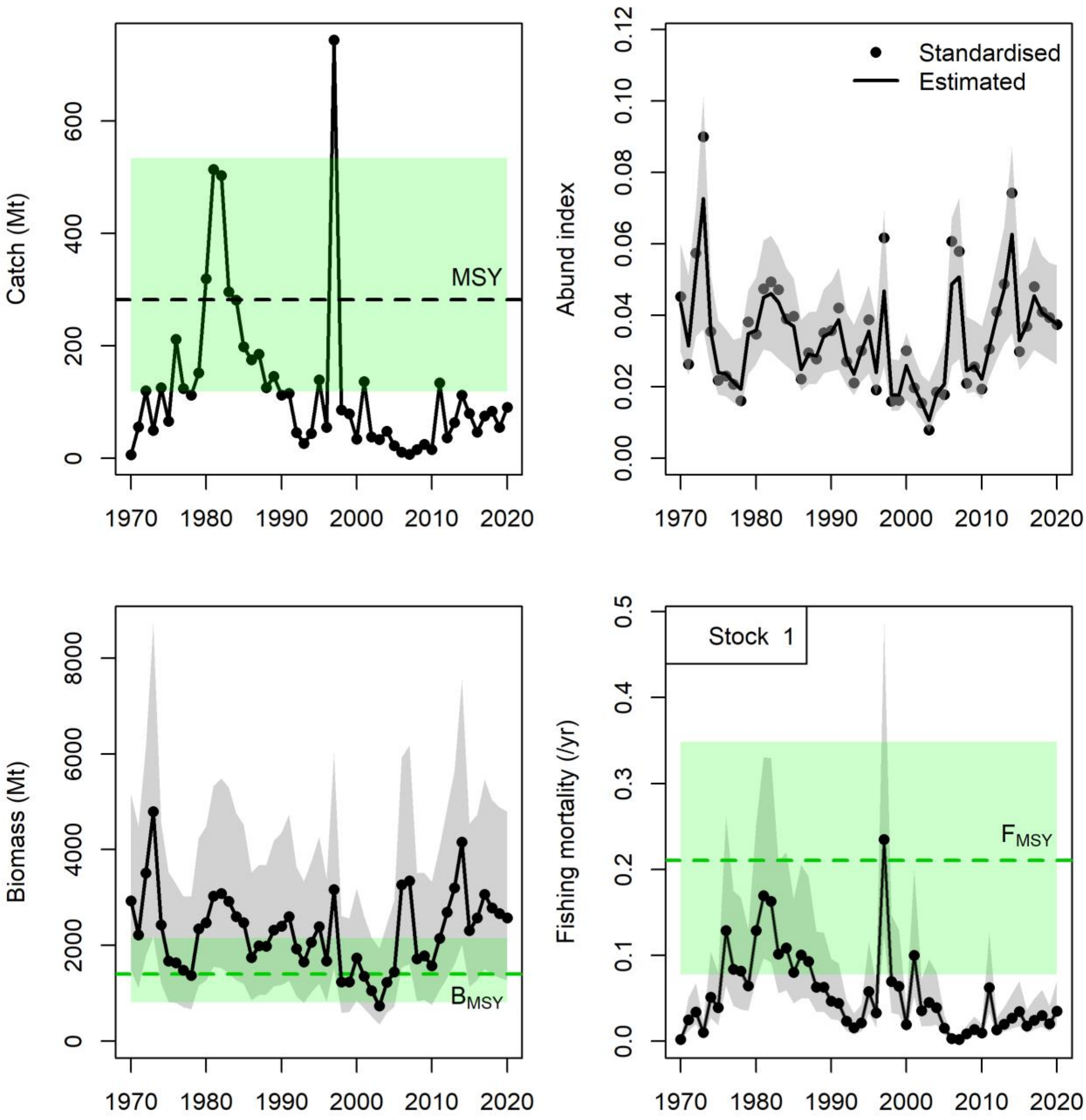

Figure 18. Result of <u>Red Endeavour Prawns</u> Stock 1. The y-axis labels in each panel denote the posteriors of the Bayesian hierarchical biomass dynamics model. The model assumes four independent stocks fished by Tiger Prawn fleet and the time series of CPUE is relative to 1995 abundance index. The error bars and the grey or green bands are 95% credible intervals.

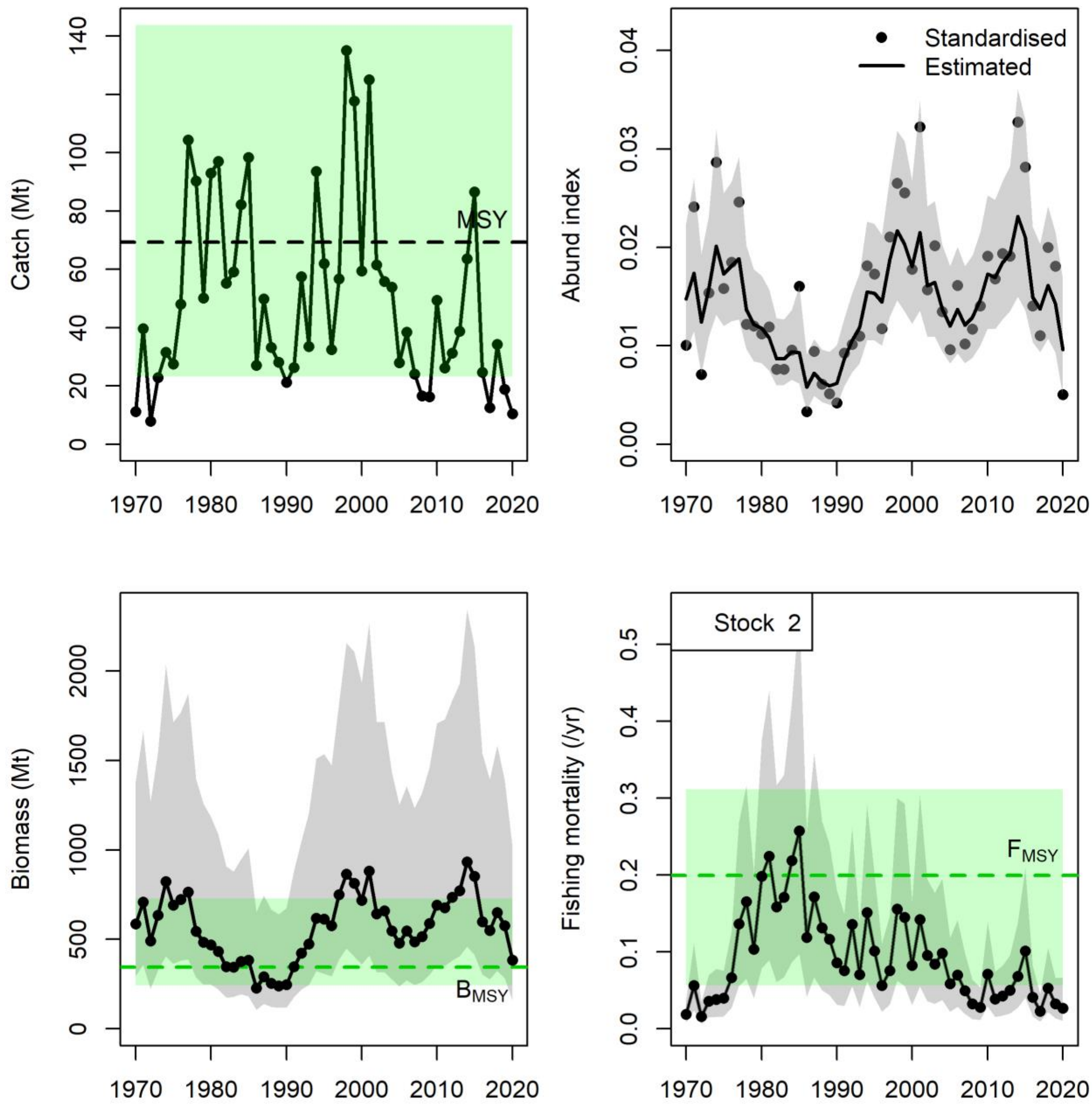

Figure 19. Result of <u>Red Endeavour Prawns</u> Stock 2. The y-axis labels in each panel denote the posteriors of the Bayesian hierarchical biomass dynamics model. The model assumes four independent stocks fished by Tiger Prawn fleet and the time series of CPUE is relative to 1995 abundance index. The error bars and the grey or green bands are 95% credible intervals.

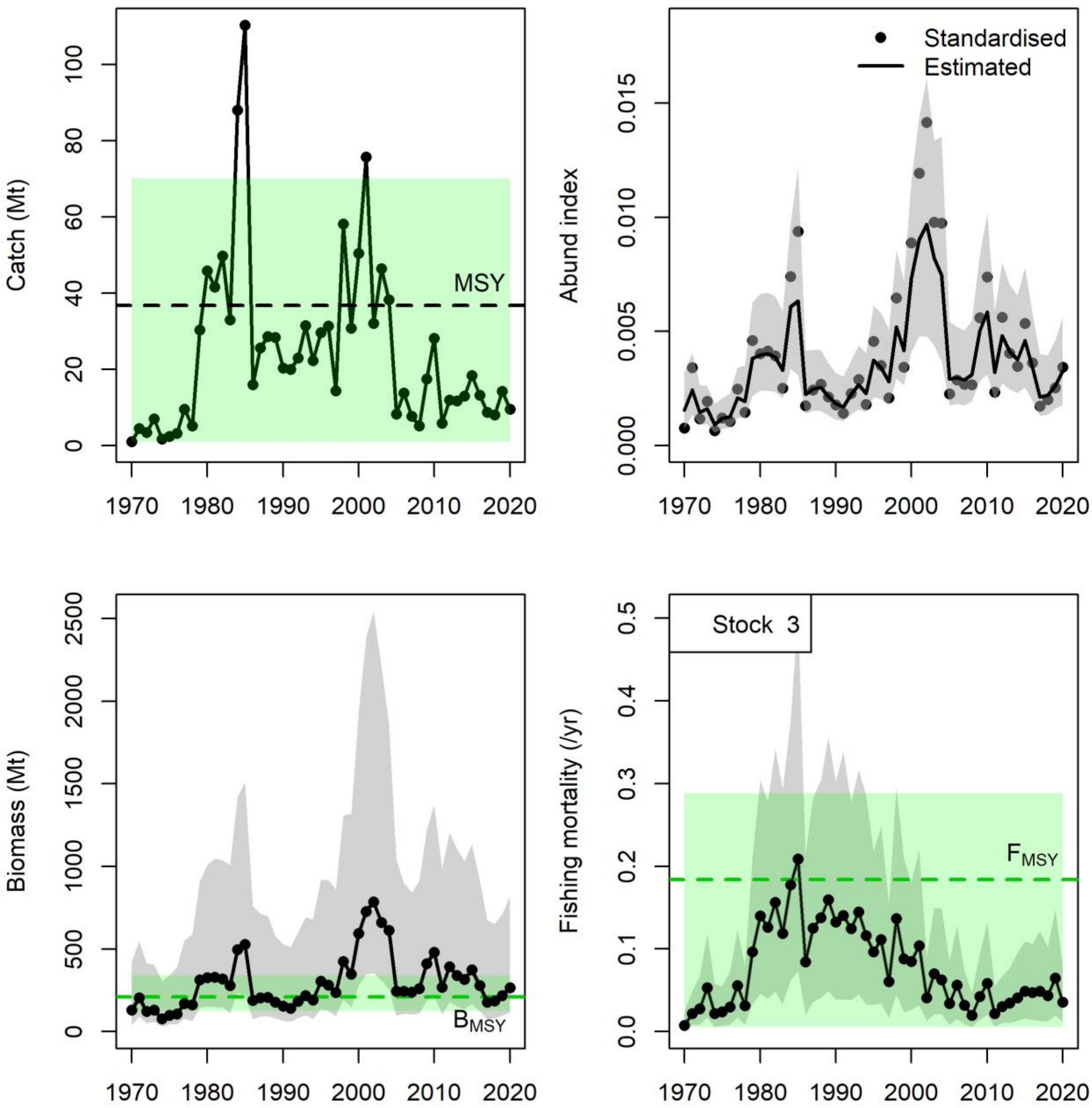

Figure 20. Result of <u>Red Endeavour Prawns</u> Stock 3. The y-axis labels in each panel denote the posteriors of the Bayesian hierarchical biomass dynamics model. The model assumes four independent stocks fished by Tiger Prawn fleet and the time series of CPUE is relative to 1995 abundance index. The error bars and the grey or green bands are 95% credible intervals.

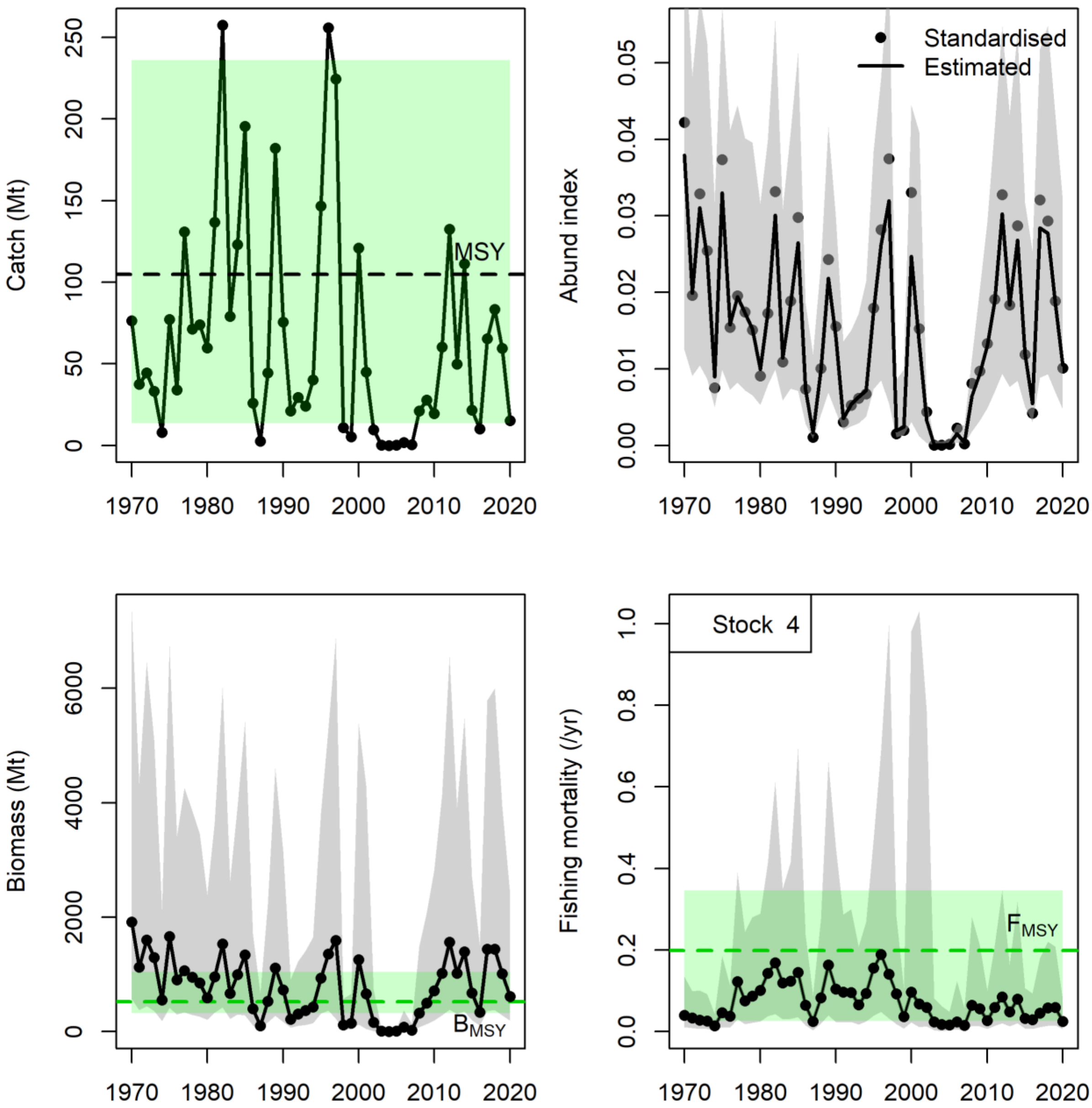

Figure 21. Result of <u>Red Endeavour Prawns</u> Stock 4. The y-axis labels in each panel denote the posteriors of the Bayesian hierarchical biomass dynamics model. The model assumes four independent stocks fished by Tiger Prawn fleet and the time series of CPUE is relative to 1995 abundance index. The error bars and the grey or green bands are 95% credible intervals.

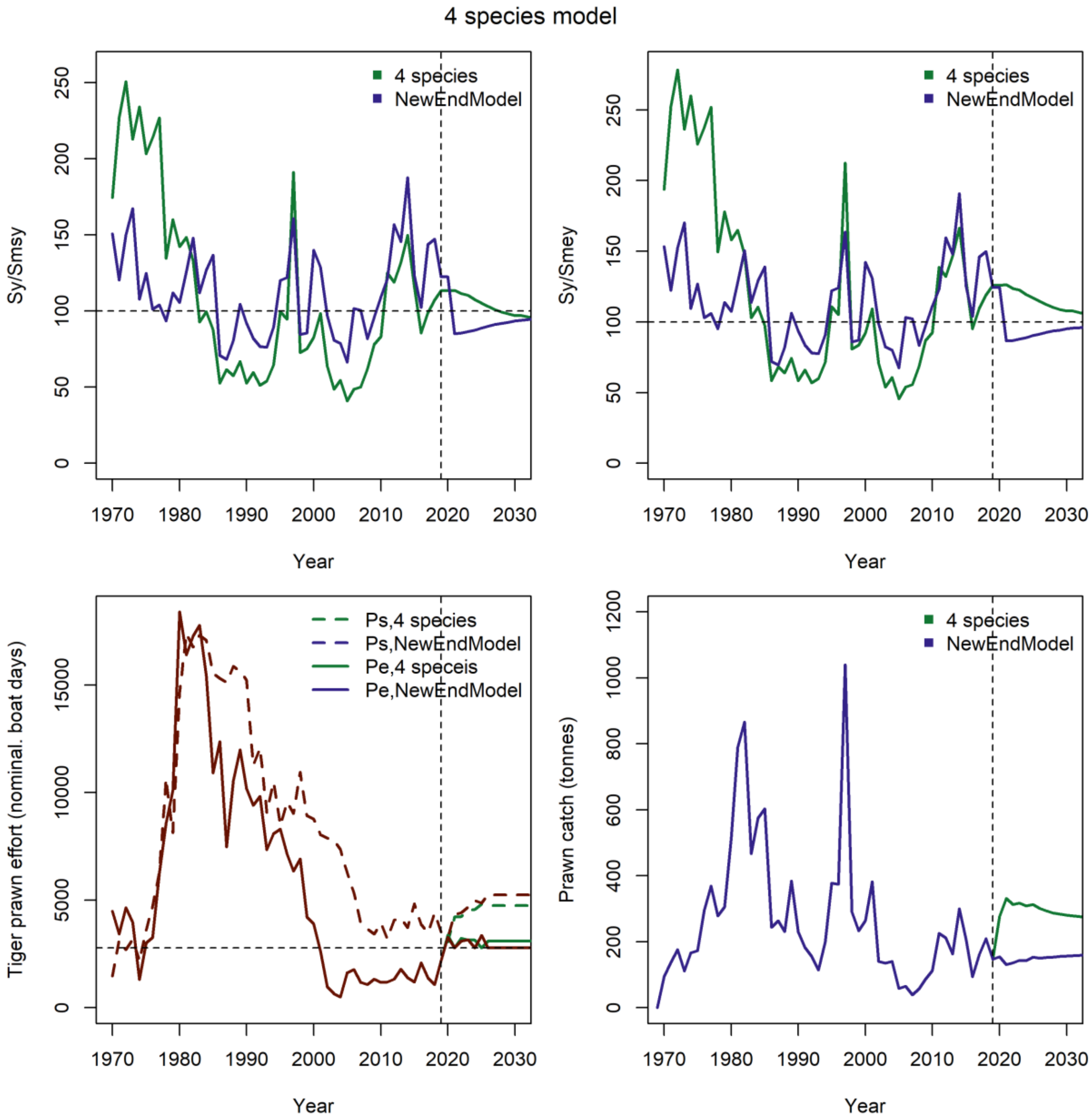

Figure 22. <u>**Red Endeavour Prawn**</u> **bio-economic model results from 4-species sensitivity test model. 4 species: Red Endeavour Prawn status from the existing 4-species model. NewEndModel: Red Endeavour Prawn status from the current assessment.**

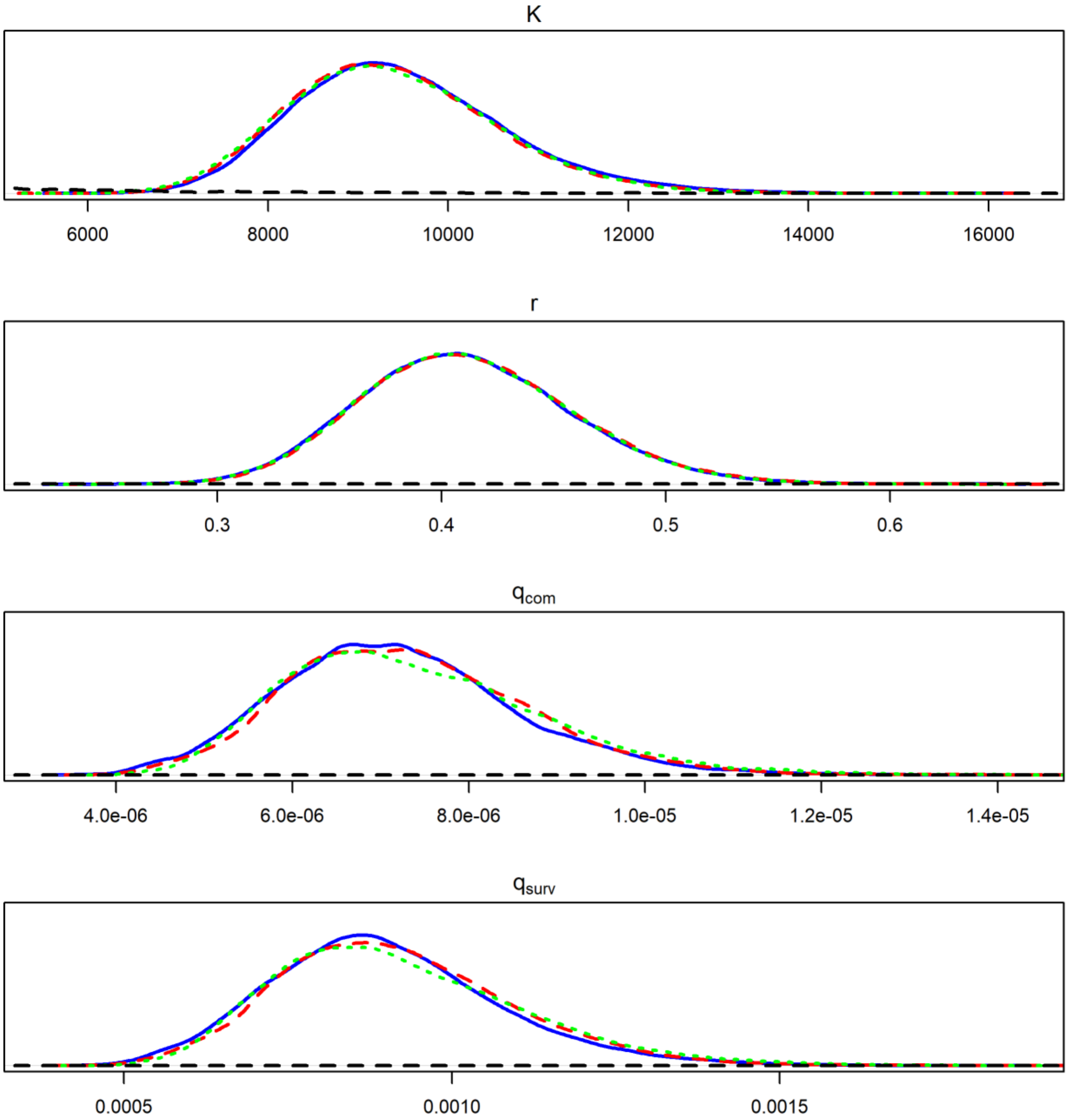

Figure 23. Posterior density distributions for key parameters (K, r, q_{com}, and q_{surv}) from the Bayesian state-space biomass dynamics model of Blue Endeavour Prawns. The three coloured lines (red, green, and blue) represent three MCMC chains and the dashed black lines are priors. The model assumes one single stock fished by Tiger Prawn fleet and uses raw catch in the logbooks.

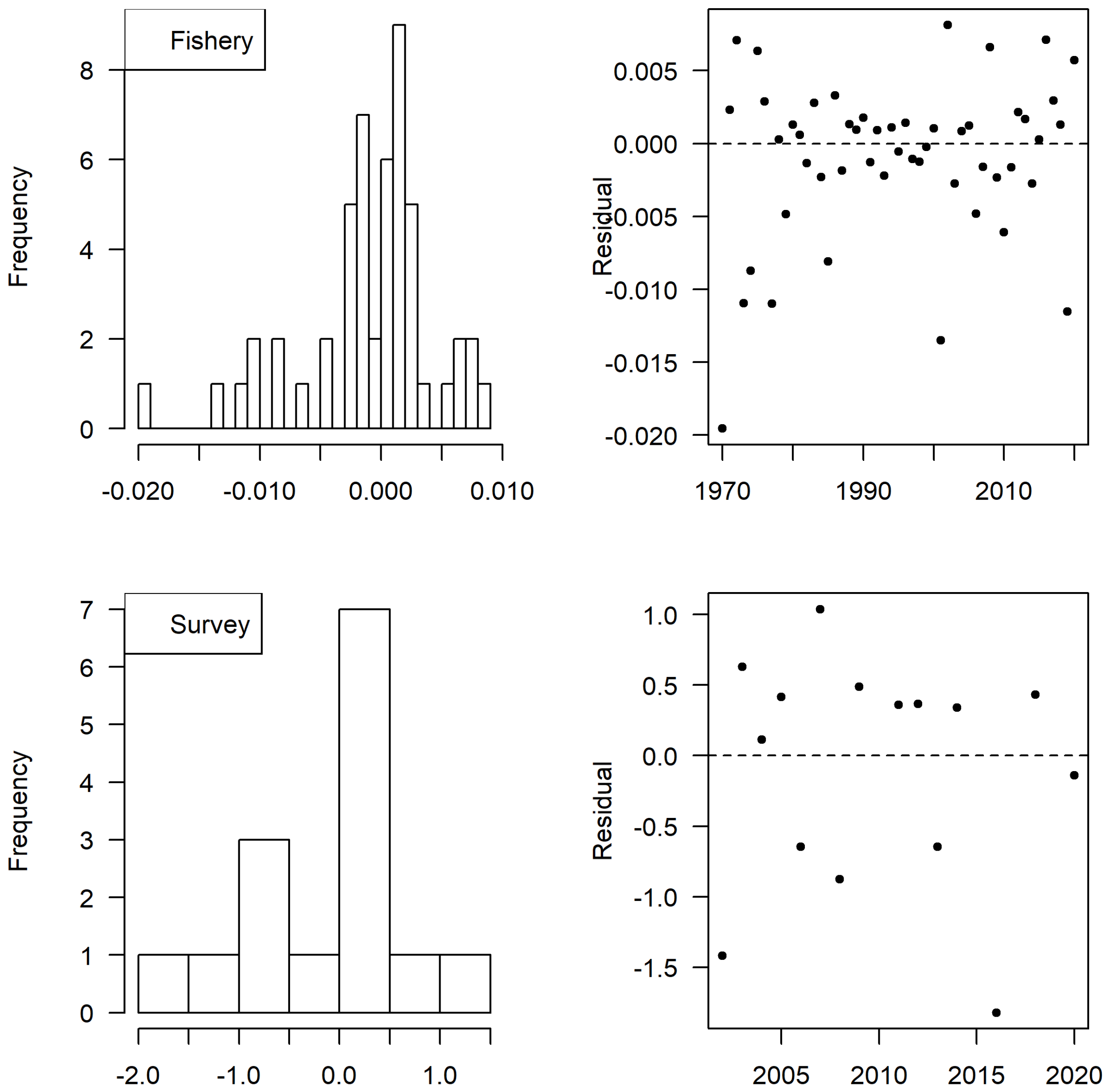

Figure 24. Residuals of Bayesian production model fitted to annual commercial standardized CPUE and spawning survey index of Blue Endeavour Prawns. The whole NPF is treated as one single stock and the raw catch from logbooks was used.

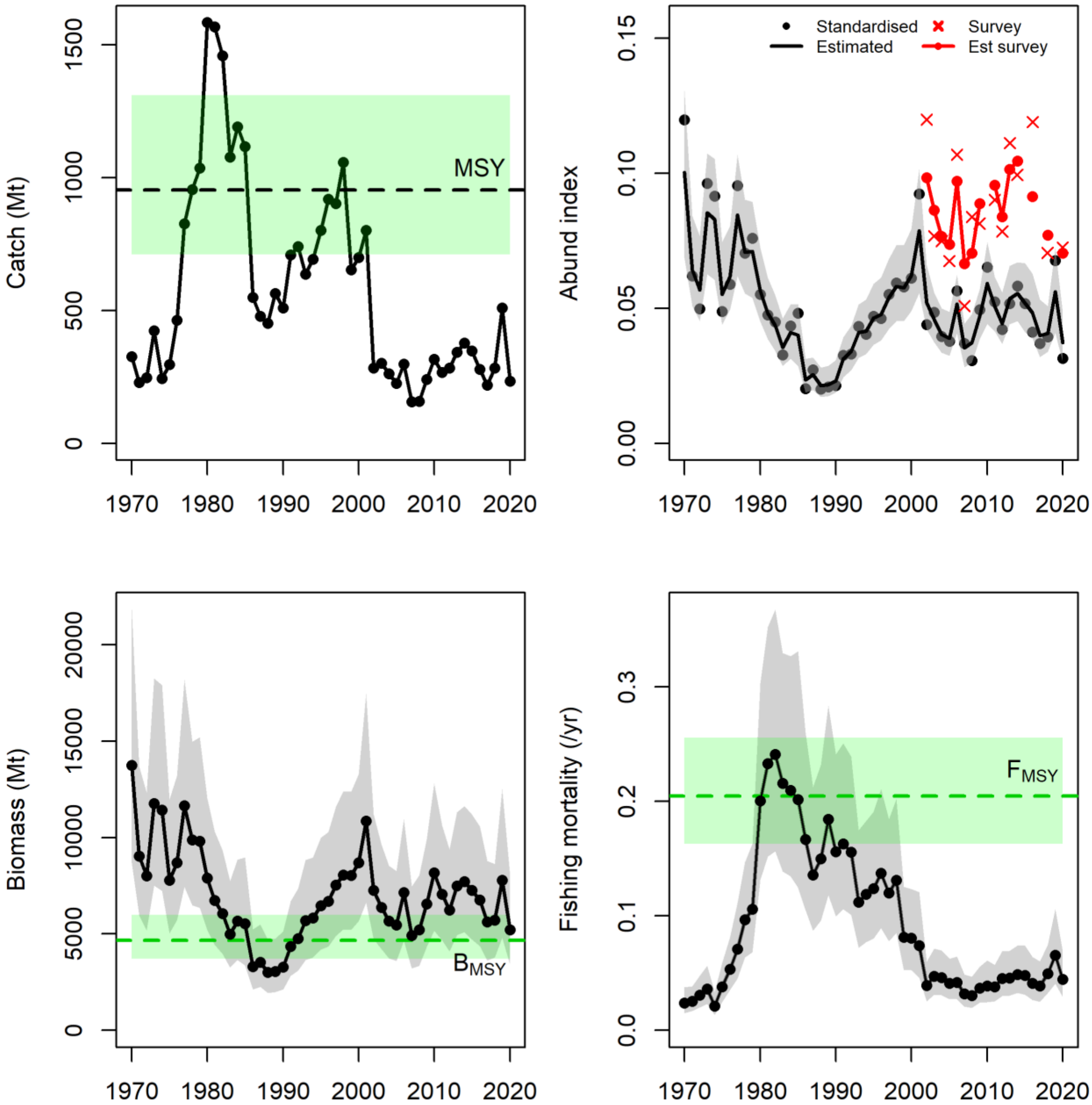

Figure 25. Result of <u>Blue Endeavour Prawns</u> from the single stock model using <u>raw catch</u>. The y-axis labels in each panel denote the posteriors of the Bayesian state-space biomass dynamics model. The model assumes one single stock fished by Tiger Prawn fleet and the time series of CPUE is relative to 1995 abundance index. The error bars and the grey or green bands are 95% credible intervals. Note the survey index has a second y-axis (scale not shown) so the plot indicates model fitting and relative pattern only but not absolute scale.

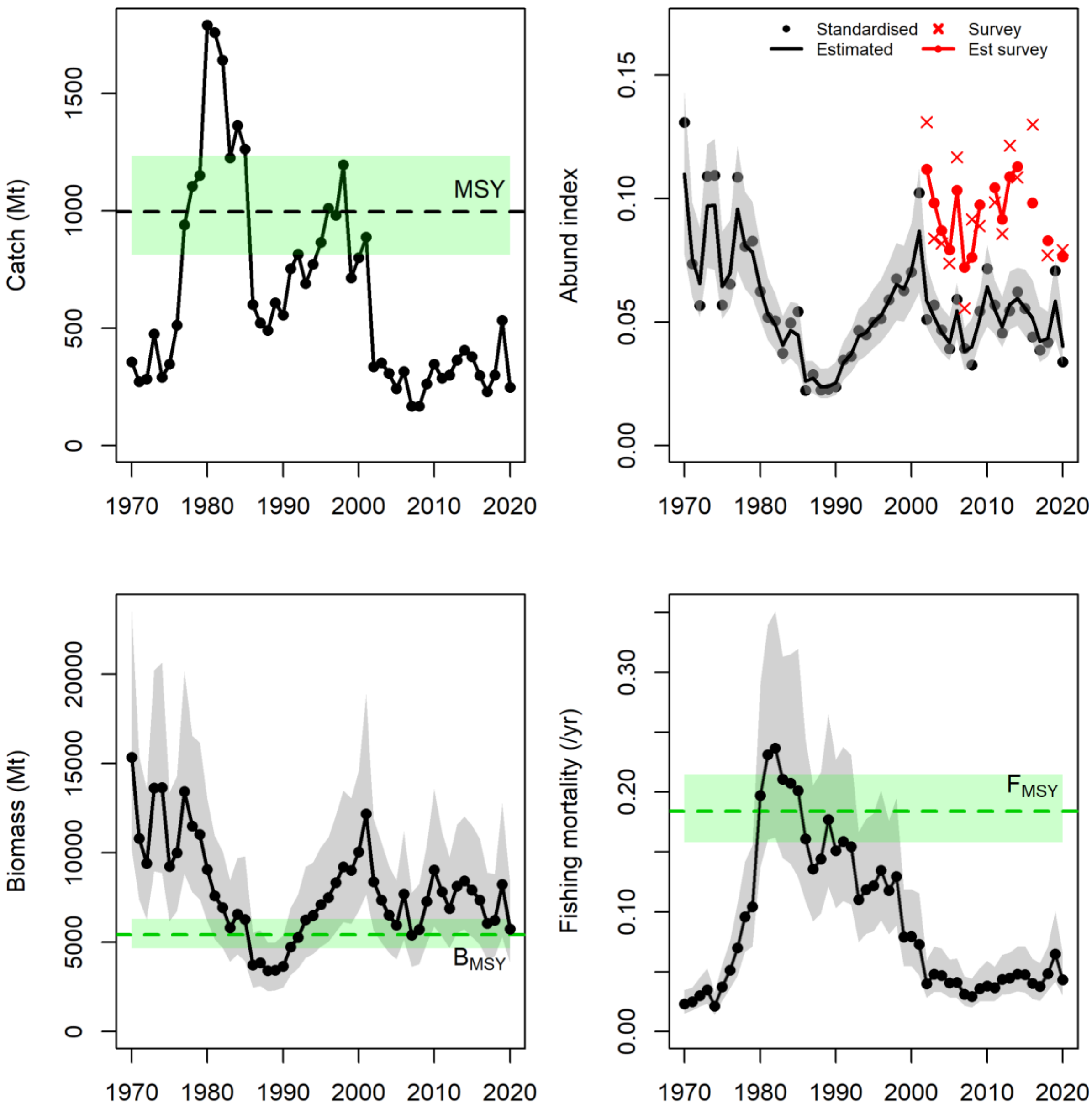

Figure 26. Result of <u>Blue Endeavour Prawns</u> from the single stock model using <u>adjusted catch</u>. The y-axis labels in each panel denote the posteriors of the Bayesian state-space biomass dynamics model. The model assumes one single stock fished by Tiger Prawn fleet and the time series of CPUE is relative to 1995 abundance index. The error bars and the grey or green bands are 95% credible intervals. Note the survey index has a second y-axis (scale not shown) so the plot indicates model fitting and relative pattern only but not absolute scale.

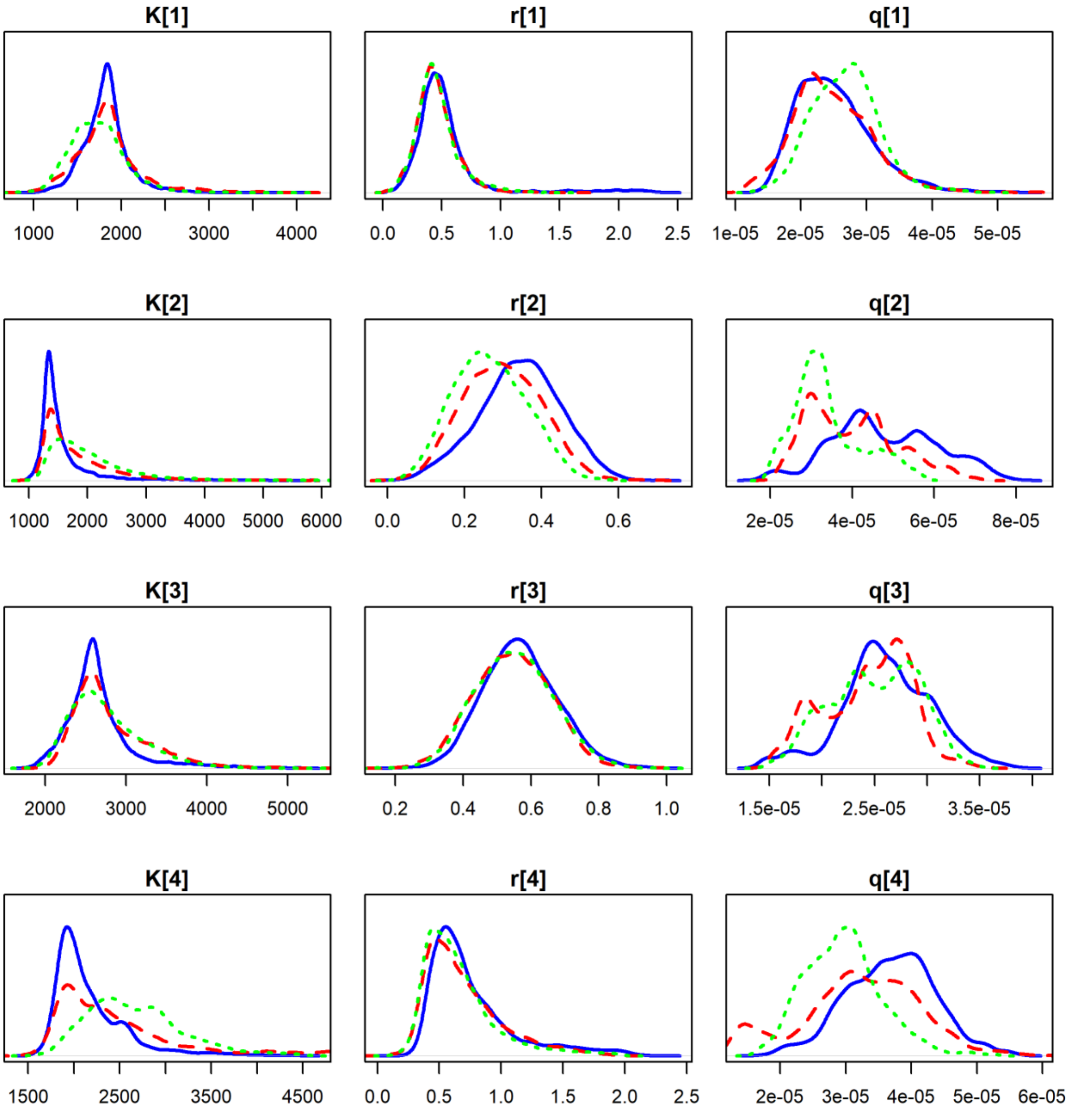

Figure 27. Posterior density distributions for key parameters (*K*, *r*, and *q*) from the Bayesian state-space biomass dynamics model of Blue Endeavour Prawns. The three coloured lines represent three MCMC chains. The model assumes four independent stocks fished by Tiger Prawn fleet and uses raw catch in the logbooks.

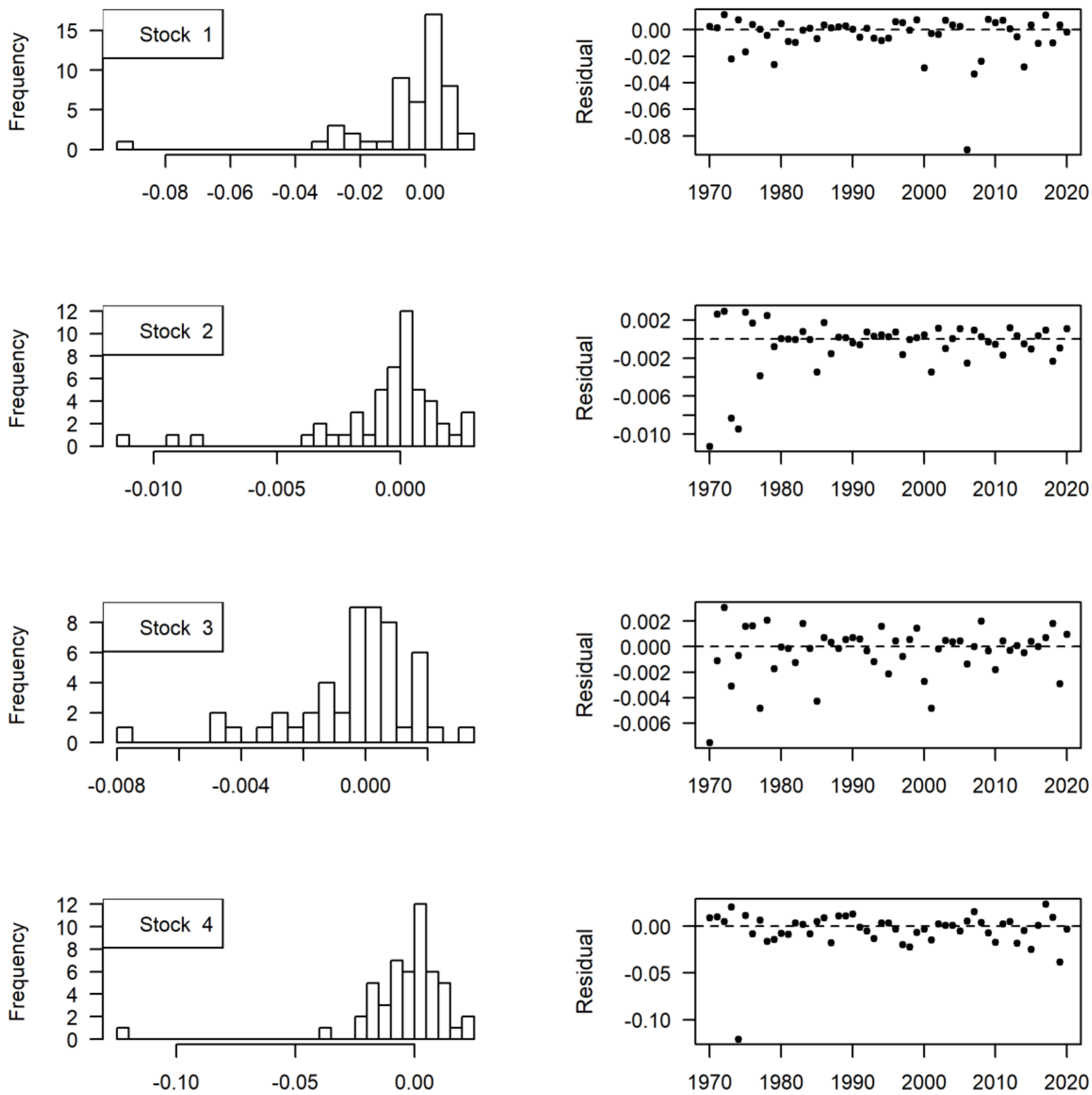

Figure 28. Residuals of Bayesian production model fitted to annual commercial standardized CPUE of Blue Endeavour Prawns. Four independent stocks are assumed in the NPF and the raw catch from logbooks was used.

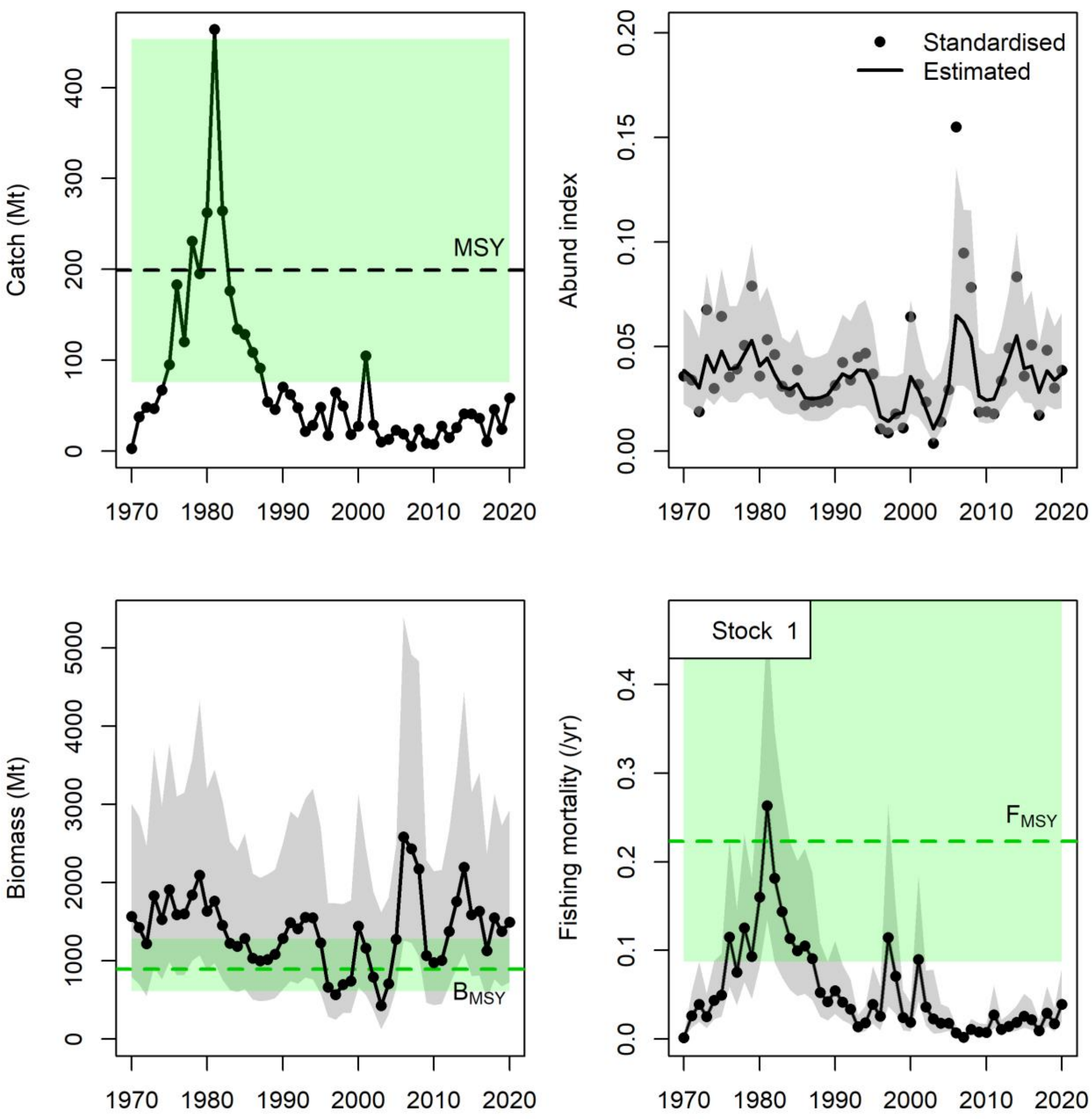

Figure 29. Result of <u>Blue Endeavour Prawns</u> Stock 1. The y-axis labels in each panel denote the posteriors of the Bayesian hierarchical biomass dynamics model. The model assumes four independent stocks fished by Tiger Prawn fleet and the time series of CPUE is relative to 1995 abundance index. The error bars and the grey or green bands are 95% credible intervals.

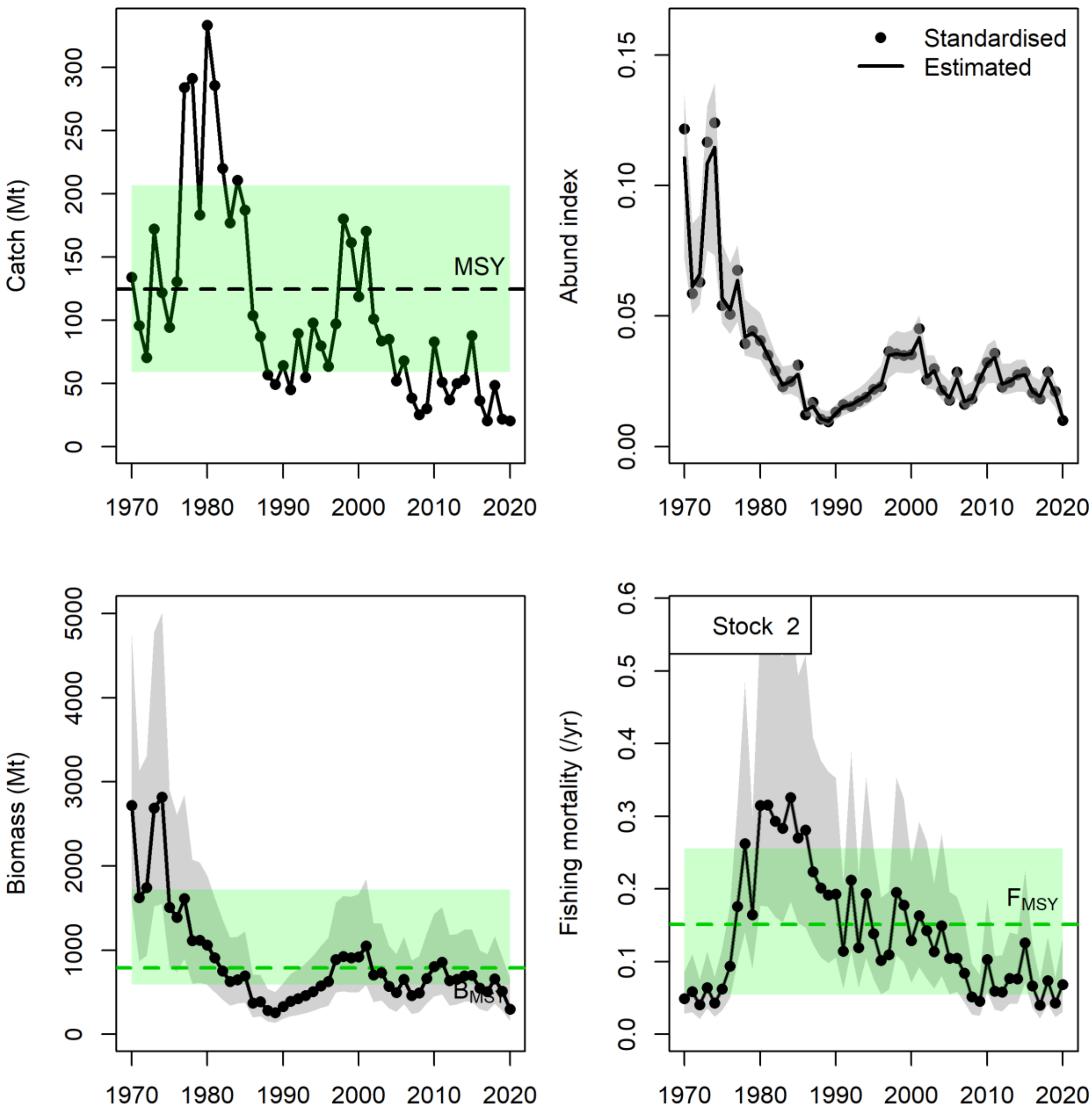

Figure 30. Result of Blue Endeavour Prawns Stock 2. The y-axis labels in each panel denote the posteriors of the Bayesian hierarchical biomass dynamics model. The model assumes four independent stocks fished by Tiger Prawn fleet and the time series of CPUE is relative to 1995 abundance index. The error bars and the grey or green bands are 95% credible intervals.

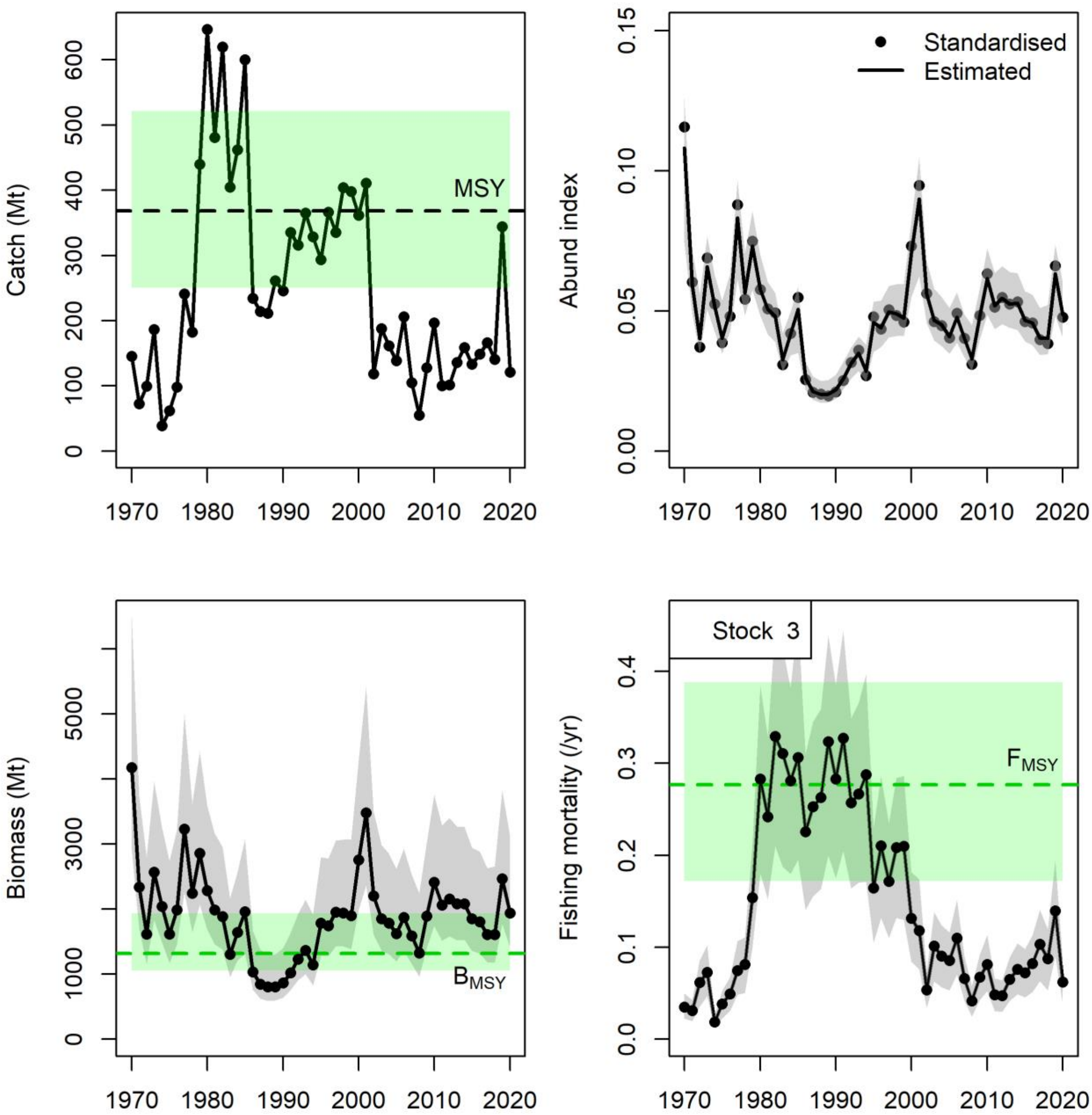

Figure 31. Result of <u>Blue Endeavour Prawns</u> Stock 3. The y-axis labels in each panel denote the posteriors of the Bayesian hierarchical biomass dynamics model. The model assumes four independent stocks fished by Tiger Prawn fleet and the time series of CPUE is relative to 1995 abundance index. The error bars and the grey or green bands are 95% credible intervals.

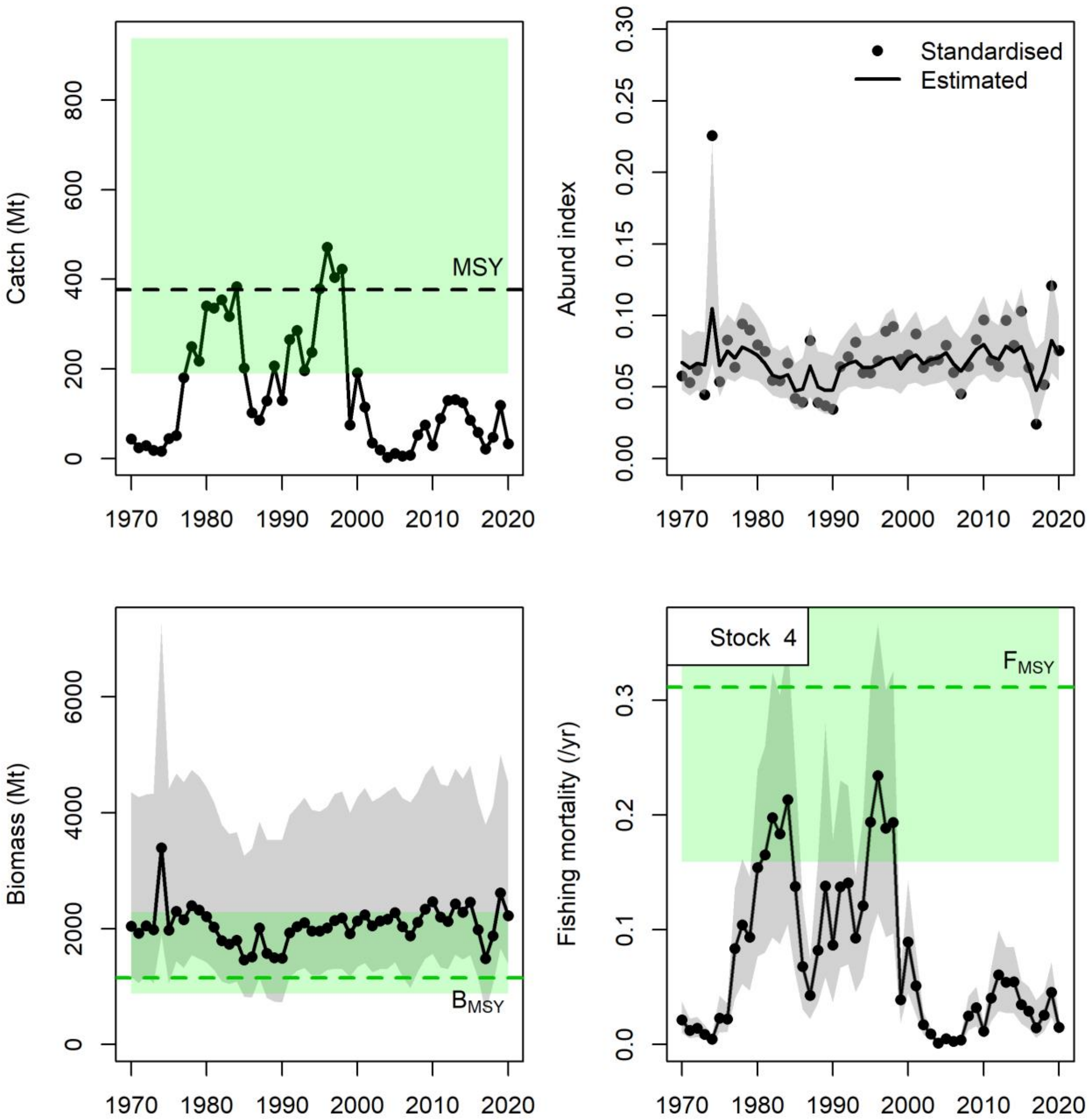

Figure 32. Result of Blue Endeavour Prawns Stock 4. The y-axis labels in each panel denote the posteriors of the Bayesian hierarchical biomass dynamics model. The model assumes four independent stocks fished by Tiger Prawn fleet and the time series of CPUE is relative to 1995 abundance index. The error bars and the grey or green bands are 95% credible intervals.

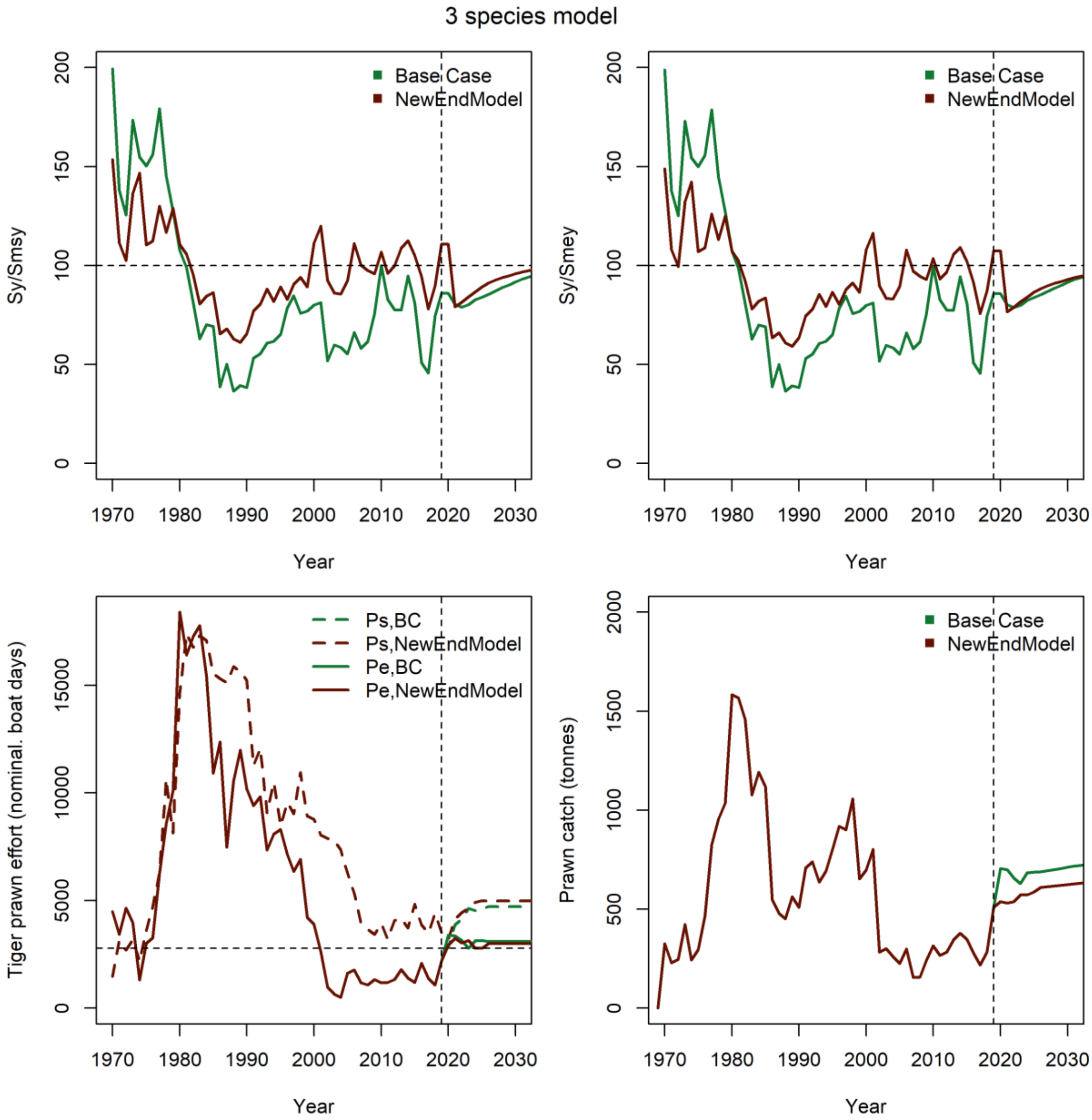

Figure 33. Blue Endeavour Prawn bio-economic model results from 3-species model. Base case: Blue Endeavour Prawn status from the existing 3-species model. NewEndModel: Blue Endeavour Prawn status from the current assessment.

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