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Catch rate standardisation for endeavour prawns (*Metapenaeus endeavouri* and *M. ensis*) in the Northern Prawn Fishery

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Executive summary

There are two species of endeavour prawns harvested in the Northern Prawn Fishery (NPF): blue endeavour prawn (*Metapenaeus endeavouri*), and red endeavour prawn (*M. ensis*). The annual catch of the group (both species combined) averages 780 tonnes during the 51 years from 1970 to 2020, contributing an average of 24% total catch of the tiger prawn fishery. Endeavour prawns are generally by-product of the tiger prawn fleet and have received much less research. This report is the first study on endeavour prawn catch per unit effort (CPUE) standardisation and fishing power analysis.

In this study we apply eight alternative statistical models for CPUE standardisation. These models are composed of four generalized linear models (GLM) and four generalized additive models (GAM). Each of the two techniques assumes two alternative statistical distributions: a delta-lognormal distribution and a Tweedie distribution. Moreover, two model structures are investigated: with or without including interaction terms of some predictor. A range of fishery and technology variables are explored for their potential inclusion as predictors and about 17 of those are finally adopted in these GLMs and GAMs.

The eight different models are applied to the two species separately and to the two species combined as a group of endeavour prawns. Furthermore, the analyses are carried out at two spatial levels: treating the population in the whole NPF area as a single stock and modelling them at four sub-stock regions. We fully investigate 32 models, resulting from a combination of different statistical models (eight), species/group (three), and regions (5). Due to the inferior performance of the GLMs, this technique is only applied to the region-wide models (treating endeavour prawns as a single stock in the NPF) and for the combined two species as a group.

The statistical models are fitted to catch and effort data from the NPF logbooks between 1970 and 2020 using R software. These fitted models are then used for CPUE standardisation based on 1,645 grids of 0.1 by 0.1 degrees that have been fished by the tiger prawn fleet during the 51 years. The models utilize both positive and zero catch records, include daily number of vessels as a predictor, and the predicted catch rates are based on the same grids every year. Hence, it is hoped that the analyses account for historical management changes that result in spatial and temporal closures and reduction in fleet size, eliminating the effect of changes in spatial and temporal distribution of fishing effort and intensity.

Several statistics are employed for model evaluation and comparison, including Akaike information criterion (AIC), deviance explained, mean squared error (MSE), and adjusted R^2. Comparing R^2 (between 0.39 and 0.44 from the GAMs) with those from tiger prawn analyses indicates that these models perform reasonably well (describe similar levels of variation within the data), given that endeavour prawns are non-target species. The results suggest that the estimated abundance index can be obtained from modelling the logbook data together with vessel information and can be used for stock assessments of endeavour prawns.

Amongst the eight different statistical models, the generalized additive models that assume a Tweedie distribution and include interaction terms generally perform the best. When this GAM model is applied to the two species combined, and across the whole NPF area, the model describes 45.8% of the total deviance and results in a MSE (in log-scale) of 0.423. However, the standardized CPUE trends from the alternative models are quite similar. The trends of the standardized abundance index over time (SI_y) from alternative models are difficult to distinguish visually and the difference in the abundance index values is small (mean CV 0.046 for four GAMs over the 51 years). Therefore, it is not critical to determine the best model and using time series of abundance index estimated by any of the four GAMs would be appropriate. The time series of SI_y indicates that endeavour prawns were more abundant in the early years but less abundant in recent years than indicated by the raw or nominal CPUE estimates. SI_y declined significantly before 1986 but slowly increased during the 1990s and since early 2000s has tended to be less variable. When the change in standardized CPUE is expressed as a change in relative fishing power FP_y, fishing efficiency on endeavour prawns has increased from $FP_{1970} = 1$ to $FP_{2020} = 2.96$ during the 51 years. The average annual creeping factor is $C\% = (2.96 – 1)/51 = 3.8\%$.

In addition to analysing the two species of endeavour prawns combined as a group, CPUE standardisation is also carried out for blue endeavour prawn and red endeavour prawn separately. Interestingly, the temporal trends of SI_y are very similar among the two species and the group. Particularly, blue endeavour prawn and the combined group exhibit nearly an identical pattern. We hypothesise that the similar results are due to the fact that endeavour prawns are recorded as a group in the logbooks but split into two species by a statistical model afterward. The proportion of one species in the group is fairly stable over time with a dominating catch of blue endeavour prawn. Hence, it is unnecessary to model two species independently. It is recommended that the results from the combined two species as a group is used in future stock assessments. It should be noted that this is inconsistent with the current application of CPUE standardization to tiger prawns where fishing power is estimated from the combined catches of two species of tiger prawns plus one half of endeavour prawn catches.

Standardizing CPUE at sub-stock level was more challenging. When the catch data are divided into four Endeavour Prawn Stock Regions, low fishing effort in some regions and years reduces model stability and makes model comparison difficult. The standardized CPUE trends are distinguishable among the four GAMs, particularly for Stock 1 and Stock 4. The delta-lognormal models with interaction terms appear to be more suitable for stock-specific catch rate standardisation. When stock assessment is conducted at multi-stock level (as in the current Bayesian hierarchical biomass production model for blue endeavour prawns), stock-specific SI_y can be adopted; otherwise, the region-wide SI_y should be used.

The results from this study are indirectly validated through comparison with estimates for other species or from other fisheries. The changes in relative fishing efficiency gauged by the mean creeping factor can be compared across studies. A preliminary study using a Bayesian state-space depletion model estimated that relative fishing efficiency of the brown tiger prawn fleet on blue endeavour prawn in the NPF only increased 0.22 times between 1970 and 2005, equivalent to less than 1% per year increase during the 35 years. In the Queensland East Coast Trawl Fishery, fishing power in harvesting the northern endeavour prawns increased by an average of 0.93% per year (13% increase from 1989 to 2003). For other species, mean annual creeping factors are 0.57%, 1.21%, 2.86%, and 0.35% for tiger prawn, red spot king prawn, east king prawn, and saucer scallop, respectively. Our estimated creeping factor of 3.8% for endeavour prawns is larger than the estimates in the Queensland East Coast Trawl Fishery, but close to the creeping factor for the white banana prawns in the NPF (3.88% per year from 1987 to 2011). Globally, most estimated creep factors are around 2–4%/yr, and our estimates is within this range. Independent estimates of changes to the fishing power for endeavour prawns would be complicated by reason of their being only a bycatch species rather than a target. Estimating changes to the catching efficiency or fishing power of effort that succeeds in taking a bycatch species may be biased for reasons relating more to the target tiger prawn fishery than the incidental catch of endeavour prawns in the areas where the distributions of the two types of prawn overlap.

The outcomes from this study, if adopted, will have important implications for stock assessment and subsequent management of endeavour prawns in the NPF. Recent assessments suggest that the stock abundance of blue endeavour prawns has been below S_{MSY} and S_{MEY} since 1980. Sensitivity tests on red endeavour prawn indicates that the stock abundance was above S_{MSY} and S_{MEY} at the end of 2019 but was below S_{MSY} in most years during the period between 2000 and 2020. Because the relative fishing power increase for endeavour prawns is slower than that of tiger prawns, using the estimates in this study will lead to higher abundance estimations in recent years than that based on tiger prawn fishing power, potentially overcoming management concerns on stock status of both blue and red endeavour prawns.

1 Introduction

Catch per unit effort (CPUE) is one of the most important types of data used in fisheries stock assessments. It is calculated by $CPUE_y = C_y/E_y = q\ B_y$, where *C* is catch, *E* is effort, *q* is catchability, *B* is stock vulnerable biomass, and the subscript *y* is year. This equation shows that if we assume that catchability *q* is constant, a time-series of CPUE can be used as an index of abundance over time. However, catchability is generally not constant, but changes spatially and temporally due to changes in fishing gear configuration, fishing tactics, technological improvement, environmental condition, and fish distribution (Arreguín-Sánchez, 1996; Salthaug and Aanes, 2003; Zhou *et al.*, 2007). Stock assessments typically require standardizing CPUE to account for factors changing other than the underlying stock abundance and thereby make the index comparable over time (Campbell, 2004, 2015; Maunder and Punt, 2004).

In the Northern Prawn Fishery (NPF), stock assessments take somewhat different approaches. Instead of conducting CPUE standardisation, the NPF derives relative changes in fishing efficiency of the fleet over time—a time series of relative fishing power (Robins *et al.*, 1998; Bishop *et al.*, 2008; Dichmont *et al.*, 2010; Punt *et al.*, 2010). This time series of fishing power is then used to adjust a constant catchability either fixed [e.g., for the grooved tiger prawn, (Wang, 1999), or estimated (Zhou *et al.*, 2009)]. Historically, the analysis of fishing power was based on two tiger prawn species (*Penaeus esculentus*, the brown tiger prawn, and *P. semisulcatus*, the grooved tiger prawn) (Dichmont *et al.*, 2003; Bishop *et al.*, 2008). This has been changed to include half of any endeavour prawn catches in each boat-day as the dependent variable in the fishing power models (Dichmont *et al.*, 2010; Deng *et al.*, 2021). The estimated time series of relative fishing power was assumed to be the same for all tiger prawn and endeavour prawn species caught in the tiger prawn fishery.

The two endeavour prawn species, *Metapenaeus endeavouri*, the blue endeavour, and *M. ensis*, the red endeavour, have been an important group of commercial species in the NPF. The combined annual catch of the group varies between 188 tonnes and 2,111 tonnes (averaging 780 tonnes) during the 51 years from 1970 to 2020. This makes up 13% to 41% (averaging 24%) of the catch of the tiger prawn fishery where the two tiger prawn species are the primary target species. Endeavour prawns are generally a bycatch of the targeted tiger prawn species by the fleet, and have received much less research. There has been no CPUE standardisation, nor fishing power analysis specifically for endeavour prawns. The current stock assessment of endeavour prawns applies fishing power derived largely from tiger prawns (the existing tiger prawn fishing power model has been based on the tiger prawn catch plus a half of endeavour prawn catch, Dichmont *et al.*, 2010). During the 51 years endeavour prawns on average make up 24% (ranging from 13% to 41%) of catches in the tiger prawn fishery. Hence, endeavour prawns only contribute about 12% in the tiger prawn fishing power analyses. Using the relative fishing power estimated primarily for tiger prawns may lead to incorrect abundance indices because these prawns have different distributions, i.e. in terms of spatial range and relative density (Venables *et al.*, 2006). For example, the availability of non-target species is generally lower than target species, which will render non-target species less vulnerable to fishing gear regardless of technological improvement and changes in the fishery. In addition, many technology variables in the fishing power model are currently treated as offsets (Dichmont *et al.*, 2010). Offsets are fixed coefficient values obtained from external evidence including expert knowledge and judgement. The fixed values are meaningful and particular to the dependent variable (i.e., tiger prawn catch), if they are correctly derived. For non-target species, such as endeavour prawns, the offset values can be different from those estimated for tiger prawns, even if the technology has a similar impact on fishing efficiency because of different local availability, different behaviours leading to different vulnerability, and other factors. For example, the use of try-gear has been very influential on the effectiveness of tiger prawn targeting, but non-target species caught in the try-gear will have far less influence on fishing behaviour.

In this study we modelled catch rates of blue endeavour prawn and red endeavour prawn species separately and the two species combined as a group. The currently tiger prawn fishing power models (Dichmont *et al.*, 2010) evolved from earlier versions (Bishop *et al.*, 2008). To be consistent with tiger prawn models and to facilitate future analyses, we adopted most the dependent variables from the current tiger prawn fishing power models. However, we focused on original data without resorting to deriving offsets. We also explored the significance of additional variables, such as fishing location, the proportion of one tiger prawn species in the tiger prawn group, and the total fishing effort in the same day. We treated the endeavour prawns as a single stock in the whole NPF area but also modelled them at sub-stock levels so that the stock-specific abundance index can be used when multi-stock spatial assessment models are implemented for the red and blue endeavour prawns. We focused on generalized linear model (GLM) and generalized additive model (GAM) techniques, as the former has been adopted for tiger prawn fishing power analysis (Bishop *et al.*, 2008; Dichmont *et al.*, 2010) while GAM has often been found more flexible and powerful for non-linear relationships between catch rate and many predictors (Tian *et al.*, 2009; Potts and Rose, 2018; Zhou *et al.*, 2019, 2020; Wiryawan *et al.*, 2020). Alternative statistical distributions, delta-lognormal and Tweedie distributions (Shono, 2008), were assumed for the catch rate data and their performance was compared for all scenarios. Furthermore, we investigated the model structures where some interactions between predictors were included or excluded. The standardised abundance index was based on all grids of 0.1 by 0.1 degrees that have been fished by the tiger prawn fleet during the time frame considered (i.e., from 1970 to 2020), and the models used both positive and zero catch records. Hence, the analyses attempted to take into account historical management changes that resulted in spatial and temporal closures and reduction in fleet size, eliminating the effect of changes in spatial and temporal distribution of fishing effort and intensity.

At the end of this report, we discuss some major issues around the study. We compared model performance with tiger prawn fishing power analysis that presumably used a better quality of data (targeted species, fewer zero catch records, and larger amount and less variable catches). The effect of targeting tactics on fishing efficiency is briefly discussed. The reliability of model output is often a concern when the ground truth is not known. One indirect validation approach is to compare the results with estimates obtained from different methods or estimates for other fisheries and species, which we included in the discussion section.

The outcome from this study, if adopted, will have important implications for any stock assessment of endeavour prawns in the NPF, as well, consequently, potential management consequences. We consider some implications and recommendations for the use of this study.

2 Materials and methods

2.1 Data source and description

Fishery data originate from the NPF logbooks that contain catch and effort data from 1970 to 2020. There are a total of 680,589 records of daily vessel specific fishing activities. The logbook data are combined with technology information that are used in tiger prawn fishing power analysis. To be consistent, we adopted the rules in tiger prawn fishing power analysis when cleaning the data:

(1) Only include fishery data in month 3, 4, 5, 8, 9, 10, 11 (i.e., two seasons from March to May and from August to November).
(2) Only include stock sub-regions of Coburg-Melville (CM), Karumba (KA), North Groote (NG), South Groote (SG), Vanderlin (VL), Weipa (WA), and West Mornington (WM).
(3) Exclude fishing days that did not catch any tiger and endeavour prawns (but include days that failed to catch endeavour prawns). These fishing efforts might be targeting banana prawns.
(4) Exclude depths deeper than 70 m (such effort data were rare and might be targeting scampi).
(5) Exclude records that do not have technology information (see below).

These rules reduce the total records from 680,589 to 545,432 (about 20% reduction). During the 51 years, tiger prawn fleet fishing activities have occurred at least once in 1,645 grids at 0.1 * 0.1 degrees resolution. About 9.7% of fishing days did not catch any endeavour prawns. The mean nominal CPUE varied among stock regions (Table 1, Figure 4). Tiger Prawn Stock Region 2 had the highest mean catch rate while Region 4 had the lowest mean catch rate (Table 1), but the catch variability was high within each region. Catch distribution appears to be different between tiger prawns and endeavour prawns (Figure 2). For example, in 1980 good catches of tiger prawns occurred in Stock Region 5 while Region 2 had high catch rates of endeavour prawns. The spatial distribution also differs between the two endeavour prawn species (Table 1). For example, no red endeavour prawn has been found in Tiger Prawn Stock Region 6, noting that the estimated species-specific catch is based on a species split model which involves modelling uncertainties (Venables *et al.*, 2006). Correlations in catch differed among the two species of tiger prawns and the two species of endeavour prawns (Figure 3). Blue endeavour prawns had a positive correlation (Pearson correlation coefficient $r = 0.37$) but a negative correlation with grooved tiger prawns ($r = -0.14$). In contrast, red endeavour prawns had a positive correlation with grooved tiger prawns ($r = 0.12$), but a negative correlation with brown tiger prawns ($r = -0.22$). Because of the large sample size (i.e., 680,589 records), all correlation coefficients were statistically significant ($p < 0.001$). The highest mean catch rate of endeavour prawns occurred in 1974 with an average of 150.4 kg/boat-day (Table 2). There were always more blue endeavour prawns than red endeavour prawns in annual catch totals (Table 2, Figure 4).

Endeavour prawns are captured in the tiger prawn sub-fishery in the NPF. Considerable effort has been devoted to model fishing power of the tiger prawn fleet (Robins *et al.*, 1998; Bishop *et al.*, 2000, 2004, 2008; Dichmont *et al.*, 2003, 2010; Bishop, 2006). It is helpful to use the data from tiger prawn fishing power research. However, there are several differences between this project and the approach for estimation of fishing power of the tiger prawn fleet, including:

(1) our primary aim is to standardise CPUE for the purpose of endeavour prawn stock assessment rather than estimating fishing power of the tiger prawn fleet catching endeavour prawns as bycatch.

(2) tiger prawn fishing power models use many offsets for technology variables. These fixed coefficient values were obtained from external evidence including expert knowledge and judgements (Dichmont *et al.*, 2010). The fixed values are specific to the dependent variable—the amount of tiger prawn catch per boat-day. For example, an offset value of 1 means that log(CPUE) should be reduced by 1. As such these derived offsets cannot be applied to endeavour prawns as the non-target species have a lower catch rate.

(3) since endeavour prawns are not distributed exactly as tiger prawns in space and time, the effect of various technology and biology factors may be different between the two groups of prawns.

(4) Varying assumptions regarding offsets have been made in the tiger prawn fleet fishing power analysis. This has led to different trends of fishing power (e.g., Base Low, Base High, Spatial High, Integrated, etc.). The fishing power analysis typically did not provide variance estimates. However, the stock assessment model for the endeavour prawns requires one time series of standardised CPUE and, ideally, its associated variance.

We obtained the NPF vessel information (i.e., their technical characteristics) from the fishing power database that contains various information about vessels and technology changes over time. The take-up of most technologies occurred during a relatively short period (Figure 5). The vessel information is linked to the logbook data either by vessel code or fishing locations and fishing time. Catch of endeavour prawns in each day by each vessel, either combined or split into blue and red endeavour prawns, were used as dependent variables. The following variables (also see Table 3) were tested as potential predictors of changes in relative abundance of endeavour prawns.

- Fishery variables: fishing month, year, calendar-day, season, tiger, psemi, pescu, prop_semi, (i.e., catch of tiger prawns either total, split into grooved and brown tiger prawns, or proportion of one species), hours_trawled, satig, local_tiger_effort, nVcode (number of vessels fishing on the same day).
- Location variables: latitude, longitude, stock_region, depth.
- Vessel technical variables: vcode, plotter, nav_accg, pc_sat, hullg, o_brdn, trygear.

These variables were largely adopted from the current tiger prawn fishing power models (Dichmont *et al.*, 2010). However, fishing location (lat and lon) and total number of vessels in a day have not been included in tiger prawn fishing power models. Spatial heterogeneity is one of the primary interests in CPUE standardisation. Although "stock region" is intended to capture spatial variability, this level of resolution is often too coarse for species with patchy distributions and for gear types that have a relatively small affected area per unit effort (Campbell *et al.*, 2017).

Trawling can quickly deplete vulnerable populations within a short fishing season (Dichmont *et al.*, 2008; Zhou *et al.*, 2011, 2015). The speed of depletion, i.e., declines in daily CPUE, is shaped by the amount of fishing effort. Hence, we included and explored the effect of the total number of vessels in a day as a predictor. This variable may also capture the effect of effort changes during the NPF history, i.e., fleet reduction from over 200 vessels to 52.

The two biological species of endeavour prawns show some remarkable parallels in their population-scale behaviour to the two tiger prawns (Venables *et al.*, 2006). The red endeavour prawn appears to be found on muddy substrates with an inshore-offshore annual migration pattern, very similar to grooved tiger prawns (Somers *et al.*, 1987; Buckworth, 1989, 1992). The blue endeavour prawn appears to be found on courser substrates with a limited migration pattern, rather like the brown tiger prawn. Apparently, it is useful to include the catch of tiger prawns as a predictor, as these species seem to co-distribute to a degree. Including the catches of other species in the CPUE standardisation models is often for the purpose of mitigating the impact of fishers targeting tactics in multi-species fisheries (Maunder and Punt, 2004; Winker *et al.*, 2014). However, if the other species are closely related in their distribution to the species of interest and are being fished down at the same time, the inclusion of these other species as explanatory variables may remove time trends in catch rate which should be attributed to the year effect (Maunder and Punt, 2004). We tested possible ways to use tiger prawn catches, e.g., total catch, catch of one species of tiger prawns, or proportion of one species, as a predictor in our models.

2.2 Statistical models and covariates selection

We used the most commonly applied methods for CPUE standardization—generalized linear models (GLM) and generalized additive models (GAM) (Campbell, 2004; Maunder and Punt, 2004; Potts and Rose, 2018;

Zhou *et al.*, 2019). The GLM assumes that the relationship between some function of the expected catch rate and the explanatory variables is linear. The general form of GLM can be expressed as:

$$\eta_i = g(\mu_i) = \beta_0 + \sum_n \beta_n x_{n,i} + \varepsilon_i \qquad \text{Equ 1}$$

where mean μ_i is the expected catch (weight of prawns) on boat-day i and is linked to the linear predictor η_i, β_0 is the intercept, β_n is a coefficient for the explanatory variable x_n, which is considered a fixed effect, and ε_i is unstructured random error [e.g., with $N(0, \sigma^2)$].

GAMs extend GLM by replacing some or all linear predictors by additive predictors:

$$\eta_i = g(\mu_i) = \beta_0 + \sum_n \beta_n x_{n,i} + \sum_m f_m(x_{m,i}) + \varepsilon_i \qquad \text{Equ 2}$$

Where f_m is a smooth function for variable x_m.

In both GLM and GAM, we need to (1) determine a sampling distribution for the response variable (catch of prawns), e.g., normal, log-normal, binomial; (2) choose a link function appropriate to the sampling distribution (e.g., identity function for normal distribution, Gaussian for log-normal distribution, and logistic for binomial distribution); and (3) select a set of independent covariates.

The catch distribution of endeavour prawns is clearly skewed. A log-transformation leads to an approximately normal distribution when catches in all years are combined (Figure 6). Therefore, we assumed that the expected catch is log-normally distributed. However, when viewed on the yearly basis, catches in log-scale can be skewed toward either side in some years (Figure 7).

Unlike tiger prawns, there are 9.73% of boat-days of effort with zero catch of endeavour prawns. To include zero values while modelling the catch as a log-normal distribution it is necessary to either use statistical models that can handle both zero and positive values, or to model the data in two parts: model the probability of non-zero catch using all the data and model the catch rate using the positive catch data only. For the first option, we used the Tweedie distribution (Shono, 2008; Foster and Bravington, 2013), while for the second option we used the delta-lognormal distribution (Maunder and Punt, 2004; Zhou *et al.*, 2019).

The delta-lognormal model is also known as the hurdle model which has two components:

$$\Pr(C = c) = \begin{cases} 1 - \pi, & c = 0 \\ \pi f(c) & c > 0 \end{cases} \qquad \text{Equ 3}$$

where π is the probability of positive catch c and is typically modelled using a binomial distribution. $f(c)$ is the distribution of positive catches, which we assumed to be a lognormal distribution: $log(c) \sim N(\eta, \sigma^2)$ (Figure 7). We tested more than 20 variables and chose the predictors by their significance in the model.

The clean dataset contains over 545,000 boat-day records. With this amount of data, models that include various covariate interactions, smoothing terms, and random effect take a great deal of computer memory and CPU. The time taken to run these models ranged from several hours to days. It is impractical to compare models using cross-validation. We opted to build the models in two steps. First, we constructed "full" models by including about 20 variables (covariates) that are adopted from tiger prawn fishing power models (Dichmont *et al.*, 2010) or likely significant predictors. After model fitting, we excluded the non-significant predictors and kept the significant ones (where $p < 0.1$) for the final model. Because most variables had been closely examined in the tiger prawn fishing power models, few variables (e.g., by-catch reduction device) were excluded from the endeavour prawn models. It is worth noting that because of the large amount of data available, nearly all variables examined were statistically significant. However, some of these variables may have little effect on the predicted trend in standardised CPUE.

2.3 Detailed models

Model 1: Generalized linear models with delta-lognormal distribution without interaction terms (GLM-DL1)

The final composition of Model 1 has the following structure:

The binomial sub-model uses a logit link:

$$\log\left(\frac{\pi}{1-\pi}\right) = year + tiger.region + month + impl1.hour + lon * lat + trygear + plotter + pc.sat + echocol + hullg + nav.accg + \log(depth) + \log(prop.semi) + \log(local.tiger.effort) + \log(satig) + \log(nVcode) + b.spline(cday, 6)$$

Equ 4

Note that we used *prop.semi*—proportion of grooved tiger prawn in the total catch of the two tiger species, which was found to be the most proper variable representing tiger prawn catches. The positive catch sub-model includes similar predictors but uses a Gaussian link:

$$\log(c) = year + tiger.region + month + impl1.hours + lon * lat + trygear + plotter + pc.sat + echocol + hullg + nav.accg + \log(depth) + \log(prop.semi) + \log(local.tiger.effort) + \log(satig) + \log(nVcode) + b.spline(cday, 6)$$

Equ 5

Model 2: Generalized linear models with delta-lognormal distribution including interaction terms (GLM-DL2)

The difference between Model 1 and Model 2 is the use of interaction terms between year and calendar day and between tiger prawn stock region and calendar day. This is similar to the tiger prawn fishing power models. The binary sub-model is:

$$\log\left(\frac{\pi}{1-\pi}\right) = year * cday + tiger.region * cday + month + impl1.hours + lon * lat + trygear + plotter + pc.sat + echocol + hullg + nav.accg + \log(depth) + \log(prop.semi) + \log(local.tiger.effort) + \log(satig) + \log(nVcode) + b.spline(cday, 6)$$

Equ 6

And for the positive catch sub-model is:

$$\log(c) = year * cday + tiger.region * cday + month + impl1.hours + lon * lat + trygear + plotter + pc.sat + echocol + hullg + nav.accg + \log(depth) + \log(prop.semi) + \log(local.tiger.effort) + \log(satig) + \log(nVcode) + b.spline(cday, 6)$$

Equ 7

Model 3: Generalized linear models with Tweedie distribution without interaction term (GLM-Tw1)

This model has the same predictors and structure as GLM-DL1 (Model 1) except a Tweedie distribution is used instead of the delta-lognormal. Since Tweedie distribution can handle zero catch, the simplified model is:

$$C = year + tiger.region + month + impl1.hours + lon * lat + trygear + plotter + pc.sat + echocol + hullg + nav.accg + \log(depth) + \log(prop.semi) + \log(local.tiger.effort) + \log(satig) + \log(nVcode) + b.spline(cday,6)$$

Equ 8

Model 4: Generalized linear models with Tweedie distribution including interaction term (GLM-Tw2)

This model has the same predictors and structure as GLM-DL2 (Model 2) except a Tweedie distribution is used instead of the delta-lognormal:

$$C = year * cday + tiger.region * cday + month + impl1.hours + lon * lat + trygear + plotter + pc.sat + echocol + hullg + nav.accg + \log(depth) + \log(prop.semi) + \log(local.tiger.effort) + \log(satig) + \log(nVcode) + b.spline(cday,6)$$

Equ 9

Similar to GLMs, there are also four GAM models.

Model 5: Generalized additive models with delta-lognormal distribution without interaction term (GAM-DL1)

The two sub-models for GAM-DL1 are:

$$\log\left(\frac{\pi}{1-\pi}\right) = year + tiger.region + month + s(impl1.hour) + te(lon,lat) + trygear + plotter + pc.sat + echocol + hullg + nav.accg + s(depth) + s(prop.semi) + s(local.tiger.effort) + s(satig) + s(nVcode) + s(cday)$$

Equ 10

and

$$\log(c) = year + tiger.region + month + s(impl1.hour) + te(lon,lat) + trygear + plotter + pc.sat + echocol + hullg + nav.accg + s(depth) + s(prop.semi) + s(local.tiger.effort) + s(satig) + s(nVcode) + s(cday)$$

Equ 11

In these equations, *s* is spline smooth and *te* is tensor product smooth.

Model 6: Generalized additive models with delta-lognormal distribution including interaction term (GAM-DL2)

The two sub-models for GAM-DL2 are:

$$\log\left(\frac{\pi}{1-\pi}\right) = year * cday + tiger.region * cday + month + s(impl1.hour) + te(lon,lat) + trygear + plotter + pc.sat + echocol + hullg + nav.accg + s(depth) + s(prop.semi) + s(local.tiger.effort) + s(satig) + s(nVcode) + s(cday)$$

Equ 12

and

$$\log(c) = year * cday + tiger.region * cday + month + s(impl1.hour) + te(lon,lat) + trygear + plotter + pc.sat + echocol + hullg + nav.accg + s(depth) + s(prop.semi) + s(local.tiger.effort) + s(satig) + s(nVcode) + s(cday)$$

Equ 13

Model 7: Generalized additive models with Tweedie distribution and no interaction term (GAM-Tw1)

$$\boldsymbol{C = year + tiger.region + month + s(impl1.hours) + te(lon, lat) + trygear + plotter + pc.sat + echocol + hullg + nav.accg + s(depth) + s(prop.semi) + s(local.tiger.effort) + s(satig) + s(nVcode) + s(cday)}$$

Equ 14

Model 8: Generalized additive models with Tweedie distribution including interaction term (GLM-Tw2)

$$\boldsymbol{C = year * cday + tiger.region * cday + month + s(impl1.hours) + te(lon, lat) + trygear + plotter + pc.sat + echocol + hullg + nav.accg + s(depth) + s(prop.semi) + s(local.tiger.effort) + s(satig) + s(nVcode) + s(cday)}$$

Equ 15

Thus, we have eight different statistical models representing various assumptions about the data distributions, model structure, and the modelling techniques for endeavour prawn catch rate analyses.

2.4 Model fitting and CPUE standardisation

The 24 models described above, i.e. GLM-DL1, GLM-DL2, GLM-Tw1, GLM-Tw2, GAM-DL1, GAM-DL2, GAM-Tw1, and GAM-Tw2, each for the three species/group (grouped endeavour prawns, blue endeavour prawns, and red endeavour prawns), were fitted to the commercial logbook data, using the R program with base and mgcv packages (Wood, 2011).

CPUE standardisation aims to derive reliable abundance indices over time. After model fitting to estimate the expected catch rates in fished locations under various observed conditions, the next step is to extract the Year effect on catch rate. The *Year* effect can be obtained from the estimated coefficient of variable *year* for simple models such as those using a log-transformed dependent variable and a normal distribution error model with no interaction terms. However, for other types of models, such as hurdle models and models with interaction terms, year effects are often based on model predictions, i.e., to predict the catch rates using the standard predictors in all combinations of *year* and *location*, including those not fished in a particular year. Since fishing effort (quantified by number of boat-days) and the total number of grids fished during a calendar year have changed markedly over the 51 years of NPF history, most grids where endeavour prawns have been captured during the entire history were not fished every year and both fishing effort and number of fished grids significantly decreased in the last two decades (Figure 8). All these grids need to be included in estimating total abundance. Unlike during model fitting, when carrying out prediction, variables that affected catch rate were kept constant across all locations and years. Under these circumstances the models predict the catch rate in all years and in all fished areas, with the predicted catch rate representing the unobserved latent abundance.

To obtain the standardized CPUE we constructed a prediction dataset covering all grids of 0.1*0.1 degrees fished by the tiger prawn fleet from 1970 to 2020. Each grid and year had the same structure and identical covariates as in Model 1 to Model 8. As the prediction covers all grids that have been fished while other predictors (except *year*) were fixed at the same value, the models predict catch rate and its variance at each location. The annual standardized abundance index by model *M* and year *y*, $SI_{M,y}$, was derived by dividing mean aggregated annual predicted catch rates $\boldsymbol{\widehat{CPUE}_{M,y}}$ by the mean of this annual predicted catch rates over the time series considered (i.e., 1970-2020):

$$\boldsymbol{SI_{M,y}} = \frac{\widehat{\boldsymbol{CPUE}}_{\boldsymbol{M,y}}}{\overline{\widehat{\boldsymbol{CPUE}}}_{\boldsymbol{M}}} \quad \textbf{Equ 16}$$

This equation ensures that the abundance index varies around the mean value of 1. Similarly, the total annual variance of the predicted catch rate is the sum of variance over all grids in that year.

2.5 Model evaluation and comparison

We examined both fitted catch rate estimates and predicted indices for the eight models, for each species/ group. Residuals between the model-fitted catch rates and the observed catch rate for each boat-day were examined visually. Multiple criteria were used to compare model performance, including the Akaike information criterion (AIC), the deviance explained by the model, the mean squared error (MSE), and the adjusted R^2.

2.6 Relative fishing power

Historically and currently, fishing power (P_y), rather than standardised CPUE, has been used in stock assessments of tiger prawns and endeavour prawns in the NPF. The general form of this application can be described as

$$\boldsymbol{F_y = qP_yE_y} \quad \textbf{Equ 17}$$

or

$$\boldsymbol{CPUE_y^{true} = qP_yB_y} \quad \textbf{Equ 18}$$

Where F_y is fishing mortality in year y, q is the constant catchability coefficient [e.g. for tiger prawns an estimated value in year 1991 from a depletion analysis (Wang, 1999)], E_y is fishing effort in year y, and B_y is biomass in year y. Here $CPUE_y^{true}$ is the assumed unbiased CPUE representing the true abundance. The usage of fishing power is equivalent to calculating fishing power by annual nominal $CPUE_y$ divided by the mean annual predicted catch rates $\widehat{\boldsymbol{CPUE}}_{\boldsymbol{y}}$ (defined as "Indirect fishing power" in Dichmont *et al.*, 2010), both scaled to unity:

$$\boldsymbol{P_y} = \frac{\boldsymbol{CPUE_y}}{\overline{\boldsymbol{CPUE}}} \Big/ \frac{\widehat{\boldsymbol{CPUE}}_{\boldsymbol{y}}}{\overline{\widehat{\boldsymbol{CPUE}}}} \quad \textbf{Equ 19}$$

Where $\overline{CPUE}$ is the mean nominal CPUE and $\overline{\widehat{CPUE}}$ is the mean of the annual predicted catch rates over the 51 years. Therefore, we can estimate fishing power changes using Equ 19, from which the predicted unbiased $\widehat{\boldsymbol{CPUE}}_{\boldsymbol{y}}$ can be calculated, an alternative option to use the results of this study for stock assessment.

The relative fishing power, FP_y, is the ratio between fishing powers in year y and in the base year which is 1970 in this case:

$$\boldsymbol{FP_y = P_y/P_{1970}} \quad \textbf{Equ 20}$$

The rate of the increase of fishing power over time, referred to as "creeping factor" $C\%$, can be expressed in several ways. Since the relative fishing power in 1970 $FP_{1970} = 1$, the total increase during a period, say between 1970 and 2020 is simply FP_{2020}. The average annual creeping factor is often calculated as: $C\% = \frac{FP_y - FP_{Base}}{nFP_{Base}}\%$, where n is the number of years between y and base year (i.e., 1970 here). This mean $C\%$ is convenient for comparison because some studies only report the total increase over a fixed period, allowing simple calculation of $C\%$. $C\%$ may also be calculated as compounding rate, regression slope of FP_y

over years, or the mean of $FP_{inc} = FP_y - FP_{y-1}$, rates relative to that of the previous year (Dichmont *et al.*, 2010; Zhou *et al.*, 2015; Palomares and Pauly, 2019).

2.7 Species consideration

There are two species of endeavour prawns in the NPF but they are recorded as a group in the raw logbooks. This grouped catch is split into blue endeavour prawn (*M. endeavouri*) and red endeavour prawn (*M. ensis*) by statistical models (Venables *et al.*, 2006). Since stock assessments for endeavour prawns are species-specific, it would be preferable to have species-specific abundance indices. We first followed the practice of tiger prawn fishing power analysis by modelling the two species as a group, i.e., based on combined total daily catch, and then carried out analyses on each species separately using the split data. To be consistent, all modelling (grouped endeavour prawns, blue endeavour prawns, and red endeavour prawns) used the same predictors and model structures as described above. This leads to a total of 24 species-model combinations (3 species/group by 8 models).

2.8 Area consideration

The Norther Prawn Fishery management area has been divided into several species-specific regions. Stock modelling and management for tiger prawns are routinely based on seven Tiger Prawn Stock Regions (Figure 9). 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 9). Therefore, we modelled CPUE at two area 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. Region-specific CPUE standardisation was only carried out for the combined two species as a group because of minor differences between the three species/group. Fishing effort varied markedly between regions (Table 4). Endeavour Prawn Region 1 had the lowest fishing effort measured by both the number of grids fished and the number of boat-days. In particular, there were only 14 boat-days fished in four grids of 0.1 * 0.1 degrees in the first year (1970) (imputed from two vessels that fished for 10 days).

3 Results

3.1 Two species of endeavour prawns as a group

3.1.1 Model comparison and selection

We fitted the eight models to the catch data of combined endeavour prawns as a group. These models can be evaluated in multiple ways, for example, between GLM and GAM, between hurdle models and non-hurdle models, and between models with and without interaction terms (Table 5). Firstly, GAMs clearly out-performed GLMs when the same statistical distribution was assumed (either delta-lognormal or Tweedie) or when the same model structure was used (i.e., with or without interaction terms). This could be seen from all criteria, including AIC, deviance explained, adjusted R^2, and MSE (Table 5). Secondly, accuracy of estimating the probability of zero catch was poorer than that for modelling the positive catch component. This was true for both GLMs and GAMs and for both models with and without interaction terms. However, the binomial sub-model had minor effect on the predicted CPUE trends. We tested the approach used in the tiger prawn fishing power analyses where records of zero catch were excluded. Using the positive catch only did not apparently change the standardized CPUE, perhaps due a small number of fishing days that failed to catch any endeavour prawns (about 10%). Thirdly, including interaction terms (*year***cday* and *stock.region***cday*) could improve model fitting. *cday* was also used the current tiger prawn fishing power models, which appeared to capture the abundance depletion process during a season that predictors *year* and *month* were too coarse. Fourthly, MSE indicated that assuming a Tweedie distribution was more appropriate than a delta-lognormal distribution. However, using AIC and deviance to compare hurdle models with non-hurdle models was problematic because the former has two sub-models while the latter only has one (but the estimated abundance index from both hurdle and non-hurdle models can be compared, for example, see Figure 12).

The comparison above and shown in Table 5 suggests that Model 8, GAM-Tw2, that includes interaction terms appears to be the best model amongst the eight models. Since the GLMs performed poorly, we focused on GAMs, particularly GAM-Tw2, in the following sections. Table 6 and Table 7 show the results of GAM-Tw2, the former for the estimated coefficients for each fixed parameter and the latter for each of smooth terms. This model explained 45.8% deviance and resulted in a mean squared error (in log-scale) of 0.423. Model diagnostics shows large variability at the individual boat-day level (Figure 10). All predictors were statistically significant. The effect of continuous variables are shown in Figure 11.

3.1.2 Catch rate prediction and CPUE standardisation

The hypothetical catch rates in each of the 1,645 grids of 0.1*0.1 degrees that have been fished by the tiger prawn fleet since 1970 were predicted using the 8 fitted models by fixing all predictors to their modes or median values except the variable *year* which was a time series from 1970 to 2020. As only one unit fishing effort was fabricated for each and all grids, the predicted catch rates at each grid were simply aggregated to obtain mean annual catch rate over the entire NPF area. Finally, this mean catch rate was standardised to get relative abundance index with a mean of 1.

Figure 12 compares relative abundance indices from four alternative GAMs, i.e., one group assuming a delta-lognormal distribution and the other group assuming a Tweedie distribution, and within each group one model without interaction terms while the other model including interaction terms. Visually, it was difficult to distinguish the four models. Indeed, the difference in the SI_y values among the four models was small (CV ranges from 0.013 to 0.084 with a mean of 0.046 over the 51 years). As such, it is not critical to determine the best model; adopting a time series of abundance indices estimated by any of the four GAMs would be appropriate. Comparing the standardised CPUE to the nominal CPUE clearly indicated that endeavour prawns were more abundant in the early years but less abundant in recent years than the raw CPUE measurements. All models indicated that abundance of endeavour prawns declined significantly before 1986 but slowly increased during the 1990s and tended to be less variable since the early 2000s. The result from the best model GAM-Tw2 (Table 8) shows that relative abundance changed from 2.32 in 1970 to 0.65 in 2020. The highest abundance (SI_{1974} = 2.64) occurred in 1974 and the lowest abundance (SI_{1986} = 0.38) was estimated in 1986.

3.1.3 Relative fishing power (FP_y)

Although deriving fishing efficiency of the tiger prawn fleet catching endeavour prawns was not essential for the objective of CPUE standardization, we went a further step and estimated the relative fishing power of the tiger prawn fleet by-catching endeavour prawns. The change in the relative fishing power can be easily compared across different fisheries and species. The general patten of FP_y changes over time was similar amongst the four GAMs for endeavour prawns (Figure 13). Overall, fishing efficiency has increased from 1970 to 1996, declined during mid 1990s and 2000s, and increased again after 2006.

FP_y was more sensitive to model assumptions and structure than SI_y. Using or not using interaction terms (i.e., between *year* and *calendar day* and between *stock region* and *calendar day*) had a stronger effect than the assumed error structure (delta-lognormal or Tweedie distribution). The FP_y trend was similar between the delta-lognormal models and Tweedie models if they used the same model configuration either with or without interaction terms.

According to the best model, GAM-Tw2, relative fishing efficiency on endeavour prawns has increased from 1 in 1970 to 2.96 in 2020. This means that assuming the abundance of endeavour prawns remains constant over the 51 years, a typical vessel with the technology and gears in 2020 can catch nearly three times more prawns than a typical vessel in 1970. The average annual creeping factor is $C\%$ = (2.96 – 1)/51 = 3.8%.

For interested readers, we included updated estimates of fishing power for tiger prawns (Deng *et al.*, 2021) in Figure 13 as a comparison with FP_y for endeavour prawns. Fishing power on tiger prawn has increased from 1 in 1970 to 6.16 in 2019, over a 6-fold increase in 50 years. The average annual creeping factor is $C\%$ = (6.16 – 1)/50 = 10.3%.

3.2 Blue endeavour prawn, *Metapenaeus endeavouri*

Blue endeavour prawns comprise a large proportion of the total catches of the two species, ranging from 47% to 87% (with a mean of 71%) on a yearly basis during the 51 years of NPF history. We carried out similar analyses on blue endeavour prawns using the same predictors and models structures as described above for the two species as a group.

3.2.1 Model comparison and selection

We focused on generalized additive models because of their superior performance over GLM. The goodness-of-fit for these models was similar to the result of combining two species endeavour prawns as a group (Table 9). The statistics of AIC, deviance explained, adjusted R^2, and MSE indicate: (1) the accuracy of estimating the probability of zero catch was poorer than that for modelling the positive catch component;

(2) including interaction terms (year*cday and stock.region*cday) could improve model fitting; (3) a Tweedie distribution was more appropriate than delta-lognormal distribution; and (4) as a conclusion, Model 8, GAM-Tw2, is the best model for modelling CPUE of blue endeavour prawns. This model explained 49.6% deviance and resulted in a mean squared error (in log-scale) of 0.457.

3.2.2 Standardised CPUE and abundance index

Standardized abundance indices were similar amongst the four alternative GAMs (Figure 14). Visually, it was difficult to distinguish the four models. Indeed, the difference in the SI_y values among the four models was small (CV ranges from 0.004 to 0.102 with a mean of 0.046 over the 51 years). Comparing the standardised CPUE to the nominal CPUE clearly indicated that endeavour prawns were more abundant in the early years but less abundant in recent years than the raw CPUE measurements indicated. Detailed results were not presented here because they were very close to the estimate for the two species combined as a group (see comparison below).

3.2.3 Relative fishing power (FP_y)

Similar to the group of endeavour prawns, changes of FP_y for blue endeavour prawns were similar amongst the four GAMs (Figure 15). According to the best model GAM-Tw2, fishing efficiency has also increased about three times during the NPF history (from 1 in 1970 to 3.0 in 2019. FP_{2020} was 2.59). This is consistent with the models for the combined endeavour prawn group which comprises mostly blue endeavour prawns.

3.3 Red endeavour prawn, *Metapenaeus ensis*

Red endeavour prawns were usually a small proportion of the total catches of the two species, ranging from 13% to 53% (with a mean of 29%) on a yearly basis during the 51 years of NPF history. The analyses on red endeavour prawns were conducted in a similar manner as the analysis for the group and blue endeavour prawns.

3.3.1 Model comparison and selection

We again focused on GAMs because of their superior performance over GLMs. Comparing the goodness-of-fit for these models was more complicated than the models for blue endeavour prawns or the group (Table 9). The statistics of AIC, deviance explained, and MSE also indicate: (1) the accuracy of estimating the probability of zero catch was poorer than that for modelling the positive catch component; and (2) including interaction terms (year*cday and stock.region*cday) could improve model fitting (but there was only minor improvement). However, although a Tweedie distribution explained more than 78% deviance, the mean squared error (MSE) was larger than those from the models assuming a delta-lognormal distribution (1.072 vs. 0.873 for the model without interaction terms, and 1.030 vs. 0.849 for the model with interaction terms). This result was likely due to a lower catch rate and more extreme values in red endeavour prawns than in blue endeavour prawns. As such, it is difficult to deem models with a Tweedie distribution were superior to models using a delta-lognormal distribution.

It is worth noting that for the binomial sub-model, the statistics of AIC and deviance explained were the same between blue and red endeavour prawns (and as well as their combined group). This is because when zero-catch was recorded in the logbooks, both red and blue endeavour were also zero after applying the species split model.

3.3.2 Standardised CPUE and abundance index

Although standardized abundance indices were similar amongst the four alternative GAMs (Figure 16), the differences amongst them were more obvious than those for blue endeavour prawns. Visually, the four models can be distinguished at least in some years. This reflects that the difference in the SI_y values among the four models was larger than that for blue endeavour prawn (CV ranges from 0.012 to 0.145 with a mean of 0.079 over the 51 years). Nevertheless, the overall SI_y trends were still fairly comparable among the four GAMs. Using one of the estimated time series of SI_y in a formal stock assessment may not make substantial difference to using any other time series

3.3.3 Relative fishing power (FP_y)

Because of the variation in standardised CPUE, the differences in the estimated FP_y amongst the four GAMs for red endeavour prawns were also greater than for blue endeavour prawns (Figure 17). It appeared that the assumed error distribution (i.e., delta-lognormal or Tweedie) had a larger effect than the model structure (i.e., with or without interaction terms). For most years the estimated FP_ys by models with the same error distribution were more similar than those with alternative error distribution. If we also choose the GAM-Tw2 model, consistent with blue endeavour prawn or the combined group, fishing efficiency has increased more than four times from 1 in 1970 to 4.65 in 2020. The average annual creeping factor is $C\%$ = (4.65 – 1)/51 = 7.2%. The highest FP_y was 4.96 in 2018.

3.4 Comparing abundance index and fishing power between species/group

We compared the estimated abundance index and relative fishing power between the three species/group: blue endeavour prawns, red endeavour prawns, and their combined group based on the best model, GAM-Tw2. The abundance index appears to be very similar among them, particularly between blue endeavour prawn and the group (Figure 18). Apparently, the similar patterns resulted from the input data: the raw catch records in the logbooks reported the two endeavour prawn species as a group, and at a later stage the catch was split into two species by a statistical model. As the estimated proportion of the catch for blue endeavour prawn (p_{blue}) did not change substantially on the annual basis (CV[p_{blue}] = 0.117), the standardized CPUE that has a mean value of 1 unsurprisingly turned out to be comparable. This was more evident between blue endeavour prawns and the combined group because of the dominant proportion of blue endeavour prawn and more variable proportion for red endeavour prawns (CV[p_{red}] = 0.283).

The time series of relative fishing power was distinguishable between the endeavour prawns treated as a group, and each of the species treated separately (Figure 19). This pattern was more evident for red endeavour prawns, likely due to more variable raw catch rate data for red endeavour prawns.

3.5 Region-specific analyses

Standardizing CPUE became more challenging when the catch data were divided into four Endeavour Prawn Stock Regions. Low fishing effort in some regions and years impaired model stability and made model comparison difficult. Some similar patterns to region-wide models can be seen (Table 10), for example: (1) accuracy of estimating the probability of zero catch was poorer than that for modelling the positive catch component. (2) including interaction terms (year*cday and stock.region*cday) could improve model fitting. However, in contrast to the region-wide models, assuming a Tweedie distribution tended to be less appropriate than a delta-lognormal distribution, indicated by MSE for Endeavour Prawn Stock

Regions 1 to 3. The Tweedie model was slightly better than the delta-lognormal model for Endeavour Prawn Stock Region 4 (i.e., combined Tiger Prawn Stock Regions 6 and 7).

The standardized CPUE trends were visually distinct among the four GAMs, particularly for Endeavour Prawn Stock 1 and Stock 4 (Figure 20, Figure 21, Figure 22, and Figure 23). The Tweedie models tended to produce more variable estimates. The outcome implied difficulties in modelling CPUE at sub-stock level and the large uncertainties of model outputs (Table 11).

Comparing the standardized CPUE trends between Endeavour Prawn Stock Regions showed that the patterns were similar for Endeavour Prawn Stock Regions 2 to 4, but Stock Region 1 exhibited a more unique and more volatile trend (Figure 24). Such a similarity or dissimilarity was more obvious when we compared relative fishing power in four Endeavour Prawn Stock Regions (Figure 25). Low fishing effort in Stock Region 1 appeared to be the major cause (Table 4).

4 Discussion

4.1 Concise summary of the study

This is the first study to model catch rate of endeavour prawns in the NPF and conduct their CPUE standardization. We have applied eight alternative models (4 GLMs, 4 GAMs, each with two models using a delta-lognormal distribution or using Tweedie distribution, and each with two models including or not including interaction terms), to three species/group (blue endeavour, red endeavour, and combined group), in the entire NPF area and four Endeavour Prawn Stock Regions. As a combination, a total of 32 models have been fully explored (GLMs were only examined at the region-wide level and for the combined two species as a group). The following conclusions can be drawn from these extensive analyses:

1. CPUE standardisation is achievable for endeavour prawns in the NPF and the relative abundance index can be obtained from modelling logbook data together with vessel information.
2. The generalized additive models that assumed a Tweedie distribution and involved interaction terms generally perform the best.
3. It is not essential to separately model catch rate by the two endeavour prawn species. Combining the two species as a group could reduce the analytical cost and reduce uncertainty.
4. Fishing efficiency of the tiger prawn fleet catching endeavour prawns has increased about three times (an average annual creeping factor of 3.8%) between 1970 and 2020.
5. It is more challenging to model CPUE at sub-stock level. Low fishing effort, especially in Endeavour Prawn Stock Region 1, leads to the stock-specific abundance index being more variable and uncertain than modelling the entire NPF area as a single stock.

This section will discuss some of the major issues around the results.

4.2 Comparing model goodness-of-fit with studies on other species

The two tiger prawn species (brown and grooved tiger prawns) are the main target species by the tiger prawn fleet in the NPF. Extensive research has been conducted to model tiger prawns CPUE and fishing power and a range of models using various covariates have been explored (Robins *et al.*, 1998; Dichmont *et al.*, 2003, 2010; Bishop, 2006; Bishop *et al.*, 2008). In these studies, the two species of tiger prawns were combined as a group and records of zero catch were excluded. It was found that realistic values could not always be obtained, because the regression factors were not orthogonal, and data on the presence of technology were sometimes unreliable or systematically incomplete. There was no single best estimation model for CPUE standardisation. Different modelling approaches (e.g., the so-called prediction models and the estimation models) could reveal different trends in relative fishing power and relative abundance. The estimated R^2 from the final five tiger prawn models varied between 0.325 and 0.534 (Bishop *et al.*, 2008). Although direct comparison of different studies and species is difficult, looking at the tiger prawn models, an adjusted R^2 between 0.39 and 0.44 from our endeavour prawn GAMs with a lognormal or Tweedie distribution seem to be within the expected range given endeavour prawns are non-target species.

The Queensland east coast trawl fishery harvests a range of species. This fishery uses trawl gear similar to NPF to capture prawn species. O'Neill and Leigh (2006) conducted CPUE standardisation on several species harvested in this fishery. Their results show that adjusted R^2 for general linear models are between 0.422

and 0.565 for tiger prawns, endeavour prawns, spot king prawns, eastern king prawns and saucer scallop. These statistics are comparable with ours.

4.3 Effect of targeting tactics on fishing efficiency

Prawns, like most fished species, do not distribute randomly over their habitats. They typically aggregate over time and space (Somers and Kirkwood, 1991). A large proportion of the NPF area may even have rare or no prawns at all. The overlap between the spatial distributions of animals and fishing activities is a major variable shaping the catchability coefficient for each species caught. CPUE standardisation focusing on targeting tactics has been increasingly investigated in recent years (Winker *et al.*, 2013, 2014; Thorson *et al.*, 2017; Okamura *et al.*, 2018). The high density areas of non-targeted species are less likely to be fished than high density areas of target species, which will lead to a lower catchability for non-target species than target species (Dichmont *et al.*, 2008). For a similar reason, increases in fishing efficiency over time will be smaller for non-target species than for target species.

4.4 Increase in fishing efficiency on endeavour prawns

Fishing power estimated in this study is a relative measure of fishing efficiency. The absolute fishing efficiency is determined by catchability coefficient q. q quantifies a fraction of the population captured by an unit of fishing effort, and is the constant of proportionality between an index of abundance and true abundance (Zhou *et al.*, 2011). A classic method to estimate q is by a depletion model—examining how quick CPUE declines over time. For example, the catchability coefficient currently used in the stock assessment of tiger prawns in the NPF was estimated using a depletion type of method more than two decades ago (Wang, 1999). Similar models, implemented using a Bayesian state-space technique, have been applied to estimate time series of q for tiger prawns from 1980 to 2007 (Zhou *et al.*, 2011). The rate of increase in q estimated by the Bayesian depletion model was comparable with the rate of increase in fishing power estimated by GLM during this period (Dichmont *et al.*, 2010; Zhou *et al.*, 2011). The same Bayesian depletion model has also been tested for estimating the tiger prawn fleet q on catching blue endeavour prawn in the NPF (Dichmont *et al.*, 2008). In most years, the CPUE of blue endeavour prawns captured by the fleet targeting brown tiger prawns clearly declined during the fishing season. The estimated time series of the catchability coefficient for the brown tiger prawn fleet on endeavour prawns was fairly constant, ranging from 1.76E-04 to 2.13E-04/yr between 1970 and 2005. This means that during those 35 years, the relative fishing efficiency of the brown tiger prawn fleet on blue endeavour prawns only increased 0.22 times, on average less than 1% per year. Although that analysis of blue endeavour prawn q was preliminary, the low increment of q over years suggested that fishing efficiency on endeavour prawns has not increased as fast as for tiger prawns.

The estimated annual creeping factor of 3.8% for endeavour prawns is long-term average over 51 years. Variation in fishing efficiency is considerable from year to year. At the early stage of the fishery, estimated fishing efficiency for endeavour prawns doubled in about six years, which is nearly identical to tiger prawn fishing power increase during the same period. In the beginning of the NPF development from late 1960s to early 1970s, relatively small boats from the east and west coasts came to the Gulf to fish prawns seasonally. The fishery grew rapidly, processing factories were built at Groote Eylandt and Karumba. The early fleet included many smaller boats than only stayed at sea for a few days. These boats did not have freezers but used other refrigeration. Around Groote in the early 1970s, there was a restricted area where only the boats delivering to the factory there were able to fish. Many of these boats had to unload every few days, so would not fish far from the Groote factory. A lot of the fishing was exploratory and a large amount of endeavours prawns were landed. The huge banana prawn season of 1974 promoted rapid increases in the size, capacity, and endurance of NPF boats. This was further stimulated by a federal shipbuilding subsidy. By the early 1980s, the exploratory phase of the fishery and its expansion to new grounds had basically finished and the ongoing trend to catch high value, large tiger prawns was well underway (R. Buckworth, personal communication). This early period of rapid development appears to have been captured by fishing power increase for both endeavour prawns and tiger prawns (Figure 13).

Scientific research on prawns biology and ecology increased in the mid-1980s (Somers and Kirkwood, 1984, 1991; Crocos, 1987; Buckworth, 1989, 1992). Industry knowledge also expanded in this period. The full long summer closure and the winter closure were both introduced in 1987. Substantial gear reductions and restrictions as well as the introduction of the daytime closure also took place at the same time, in response to a drastic downturn in tiger prawn catches and the likelihood that tiger prawns might have been overfished (R. Buckworth, personal communication). Although endeavour prawns are not usually caught in the day, changes in fishing effort distribution might still have an effect on endeavour prawn catches.

Similarly, extensive fleet reduction began in the 1990s. During this period, fishing vessels rapidly installed various technological devices, including plotter, navigation instrument, personal computer with satellite connection, and echo-sounder, allowing increased targeting prawns at a fine scale. The line fishing technique that highly targets at tiger prawns also developed in this period.

Another NPF fleet reduction occurred in 2007, which could further affect effort distribution and fishing behaviour. Hence, over the NPF history there appears to be three distinct periods pre-1987, 1988 to 2007, and after 2007 (R. Buckworth, personal communication). These management changes and technology uptakes seem to be manifested well by “swept area performance rate” (satig, Figure 5) that is estimated by an engineering model, the Prawn Trawl Performance Model (Sterling, 2005). It is worth noting that the estimated creeping factor is not only determined by technology changes but is also affected by variation in spatial and temporal distributions of prawns and fishing effort. Nevertheless, it is difficult to derive unbiased abundance index and to estimate accurate creeping factor. Some important variables may have been omitted from our models.

4.5 Comparing fishing efficiency increase across species and fisheries

Several comparisons of changes in fishing power can be made across species and fisheries. We first look at the Queensland east coast trawl fishery, that harvests several invertebrate species. O’Neill and Leigh (2006) showed that for the complete fishing years from 1989 to 2003, linear mixed models estimated fishing power increases of 8% in tiger prawns, 13% in the northern endeavour prawns, 17% in the red spot king prawns, 40% in the eastern king prawn and 5% in the saucer scallop sector. These figures translate to an average annual fishing power increase of 0.57%, 0.93%, 1.21%, 2.86%, and 0.35% for tiger prawn, endeavour prawn, red spot king prawn, eastern king, and saucer scallop, respectively. The values here are smaller than our estimated 3.8% annual fishing power increase for the grouped two endeavour prawn species. Compared to our estimates, similar low estimates were reported in an earlier study of the Queensland trawl fishery (O’Neill *et al.*, 2003). During the 11 years from 1989 to 1999, fishing power for an average vessel increased at a low of 4% in the saucer scallop sector to a high of 27% in the shallow-water eastern king prawn sector, i.e., an average between 0.36% and 2.45% increase per year.

Using a population depletion analysis, Zhou *et al.* (2015) estimated biomass, catchability, and natural mortality for the white banana prawn (*Penaeus merguiensis*) in the NPF. In addition, they directly derived fishing power change over time. The models were implemented in a Bayesian framework by incorporating process error, observation error, and random variability for the underlying parameters. The median catchability was estimated to vary from 3.8×10^{-4} to 7.3×10^{-4} boat-day^{-1} during the 24 years from 1987 to 2011, converting to an average fishing power increase of 3.88% per year (expressed as logistic regression slope of 2.6% per year). This rate of fishing power increase in banana prawns is directly comparable to our work; only slightly larger than our estimated 3.8% for endeavour prawns.

The estimates of the slow increase of fishing efficiency due to technological improvement is often referred to as “creep factor”. Palomares and Pauly (2019) reviewed creeping increase of vessel’s fishing power worldwide. They found hundreds of studies relevant to fishing efficiency or fishing power and obtained 51 useable case studies with estimates of the annual increase of fishing power or fishing efficiency. These studies, covering periods from 4 to 129 years, show that most estimated creep factors were around 2–4%

per year. Our estimated 3.8% annual fishing power increase for the endeavour prawn group is within this range. These comparisons may be considered as an indirect, though insufficient, validation of the reliability of our study.

4.6 Catch rate of non-target species as abundance index

Using CPUE, whether raw or standardized, as an abundance index requires the assumption that the CPUE is proportional to stock abundance over a whole exploitation history and an entire geographic range. Because numerous factors can affect catch rates (Maunder *et al.*, 2006), raw CPUE typically needs to be standardized. Besides a range of factors that can bias CPUE as an index of abundance for target species, spatial distribution can be a particular problem for standardizing CPUE of non-target species. For instance, if majority of non-target species is distributed outside of the fishing area, catch rates within the fishing ground of target species, even after standardisation, can hardly represent the abundance of the entire stock. To use the results of this student for endeavour prawn stock assessment requires an implicit assumption that fishing grounds trawled by the tiger prawn fleet encompass all or majority of endeavour prawn habitat. As endeavour prawns and tiger prawns do not have a high correlation but do overlap in their distributions (Figure 3), we expect the standardised CPUE in this study, though potentially biased, reflects the true abundance of endeavour prawns more closely than that based on tiger prawn fishing power.

4.7 Implications for stock assessment and management

The NPF currently applies a multispecies, weekly sex- and size-structured population model for stock assessment of tiger prawns and a Bayesian hierarchical biomass production model for blue endeavour prawns (Hutton *et al.*, 2018; Deng *et al.*, 2021). In addition, the assessment includes an economic model that calculates profit (the “Base case” model). As a sensitivity test and model improvement, assessment of red endeavour prawns was performed using the same Bayesian hierarchical biomass production model as used for blue endeavour prawns.

The most recent assessment (Deng *et al.*, 2021) suggested that in all the sensitivity tests, the stock abundance of blue endeavour prawns was under S_{MSY} at the end of 2019 (from 84% to 113 %). The five-year average abundance estimate ranged from 66% to 87% of S_{MSY}. Furthermore, the operational objective of the Commonwealth Fisheries Harvest Strategy Policy (DAWR, 2018) is to attain long term Maximum Economic Yield (MEY). The key bio-economic model results for the Base Case indicated that stock size of blue endeavour prawns was below S_{MEY} for all years since 2000. These stock estimates below the target reference point of S_{MEY} for a long period have become a management concern.

Stock assessment models for red endeavour prawns have not been formally developed. Using the same Bayesian hierarchical biomass production model for blue endeavour prawns, the sensitivity tests on red endeavour prawns indicated that the stock abundance was above S_{MSY} at the end of 2019 (Deng *et al.*, 2021). The five-year average abundance was estimated to be 104% of S_{MSY}. However, this preliminary analysis also showed that stock size was below S_{MSY} in most years during the period between 2000 and 2019.

It is anticipated that the current stock assessment results will change if the standardized abundance index estimated in this report is adopted in stock assessment models. Because the relative fishing power increase for endeavour prawns is slower than that for tiger prawns, the estimated stock size in recent years will therefore be higher than the current estimates, potentially overcoming management concerns on stock status of both blue and red endeavour prawns.

4.8 Conclusions

An abundance index is a direct input into stock assessment models of endeavour prawns in the NPF. The results of stock assessment depend on the unbiased time series of abundance index for each species. The current practice of applying fishing power primarily from tiger prawn data to endeavour prawns is likely to overestimate abundance in the earlier years but underestimate abundance in recent years. We recommend that the standardized CPUE from this study be used in future endeavour prawn assessments in the NPF, instead of adjusting nominal CPUE by tiger prawn fishing power. The estimates for the combined two endeavour prawn species as a group are preferred over the results of species separated analyses; these estimates can be applied to either blue or red endeavour prawns or their combined group. If endeavour prawns in the whole NPF area is treated as a single stock, the standardized CPUE and fishing power based on the whole region should be used. On the other hand, if the stock assessment is conducted at sub-stock level, the stock-specific estimates should be adopted. However, due to high model uncertainty in some regions (e.g., Endeavour Prawn Stock 1), abundance indices from region-wide models can be employed as an alternative or sensitivity test.

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Table 1. The NPF logbook summary of endeavour prawn catch and fishing effort in each of the tiger prawn stock region from 1970 to 2020. Stock ID: the four Endeavour Prawn Stock Regions used for stock assessment. Mean, sd, and Median: statistics of the nominal CPUE (kg/boat-day). n: fishing effort in number of boat-days. Proportion: catch proportion of one species of endeavour prawn among the two species.

Stock ID	Tiger region	Mean	sd	Median	n	Proportion
	Endeavour prawn					
1	2	121.3	127.4	85.0	36,311	
2	4	41.0	49.8	26.0	160,976	
3	5	49.4	58.6	30.0	236,797	
4	6	79.4	82.7	56.0	64,206	
4	7	86.4	85.0	63.0	47,142	
Mean or total		75.5	80.7	52.0	545,432	
	Blue endeavour					
1	2	46.4	68.3	19.4	36,311	38%
2	4	26.6	36.3	15.5	160,976	65%
3	5	44.6	54.0	26.0	236,797	90%
4	6	79.3	82.6	56.0	64,206	100%
4	7	19.2	25.1	11.7	47,142	22%
Mean or total		43.2	53.3	25.7	545,432	63%
	Red endeavour					
1	2	74.87	99.60	38.94	36,311	62%
2	4	14.34	26.35	6.20	160,976	35%
3	5	4.78	11.88	0.85	236,797	10%
4	6	0.07	0.13	0.03	64,206	0%
4	7	67.26	68.51	47.79	47,142	78%
Mean or total		32.3	41.3	18.8	545,432	37%

Table 2. Summary of annual fishing effort (n: boat-day), and nominal CPUE (kg/boat-day) of total, blue and red endeavour prawns.

	Endeavour				Blue				Red		
year	Mean	sd	n		Mean	sd	Proportion		Mean	sd	Proportion
1970	81.6	67.2	3,736		63.7	55.4	78%		17.9	51.6	22%
1971	55.6	56.4	3,942		34.8	37.3	63%		20.8	40.6	37%
1972	50.0	45.1	4,026		32.6	34.5	65%		17.4	34.8	35%
1973	68.7	55.8	3,278		52.1	55.0	76%		16.6	25.2	24%
1974	150.4	125.5	1,796		88.8	71.6	59%		61.6	105.9	41%
1975	79.8	69.6	4,009		44.9	49.7	56%		34.8	47.3	44%
1976	121.4	130.4	4,115		69.9	83.2	58%		51.5	91.9	42%
1977	108.3	108.3	6,544		74.3	78.2	69%		34.0	68.2	31%
1978	65.7	82.8	10,512		50.1	68.6	76%		15.5	32.0	24%
1979	81.7	80.2	10,801		61.7	61.3	76%		20.0	49.9	24%
1980	68.2	68.9	18,363		50.2	53.2	74%		18.0	42.2	26%
1981	69.2	74.8	18,899		41.5	45.8	60%		27.7	56.2	40%
1982	67.2	74.8	20,987		42.4	52.0	63%		24.8	52.8	37%
1983	37.6	44.3	22,476		27.9	39.2	74%		9.7	24.0	26%
1984	50.0	54.6	20,734		33.4	38.7	67%		16.6	36.6	33%
1985	69.7	70.6	18,677		42.6	49.8	61%		27.0	47.3	39%
1986	27.8	39.8	19,704		18.4	24.9	66%		9.4	28.4	34%
1987	27.9	40.7	19,286		19.3	31.3	69%		8.6	25.5	31%
1988	23.7	29.8	22,351		16.4	20.7	69%		7.3	20.8	31%
1989	34.1	38.3	23,469		20.9	25.5	61%		13.3	30.1	39%
1990	27.2	30.8	21,688		19.4	25.2	71%		7.8	19.7	29%
1991	42.6	54.0	19,099		34.8	47.9	82%		7.8	29.3	18%
1992	39.7	41.6	19,796		33.6	41.6	85%		6.1	13.5	15%
1993	44.9	52.0	14,416		38.6	50.7	86%		6.3	14.6	14%
1994	47.2	54.3	17,284		37.5	51.4	80%		9.6	23.7	20%
1995	64.5	73.6	15,151		46.7	59.0	72%		17.8	47.8	28%
1996	77.1	75.8	15,151		55.2	68.7	72%		21.9	45.8	28%
1997	90.1	96.4	12,766		60.4	68.9	67%		29.7	72.8	33%
1998	75.5	63.8	15,561		59.7	57.5	79%		15.8	32.7	21%
1999	65.5	65.8	11,887		51.6	60.4	79%		13.9	31.0	21%
2000	76.4	66.9	11,900		56.6	56.5	74%		19.8	39.2	26%
2001	106.2	108.5	9,330		76.0	77.8	72%		30.2	57.6	28%
2002	47.8	47.3	7,805		33.8	38.2	71%		14.1	22.6	29%
2003	52.5	50.1	7,586		38.3	40.1	73%		14.2	24.2	27%
2004	48.1	56.3	7,146		35.0	44.1	73%		13.1	19.7	27%
2005	33.0	37.6	7,261		27.9	35.9	85%		5.1	9.2	15%
2006	50.5	59.2	6,515		42.3	53.8	84%		8.2	21.6	16%
2007	37.8	49.4	4,756		31.3	46.9	83%		6.6	11.6	17%
2008	44.8	53.5	4,259		33.8	47.5	75%		11.0	27.7	25%
2009	66.6	87.4	4,414		52.0	78.3	78%		14.6	34.6	22%
2010	86.0	90.1	4,594		65.1	78.4	76%		20.9	37.1	24%
2011	92.8	94.4	3,639		64.1	71.1	69%		28.7	63.6	31%
2012	95.6	111.6	4,828		55.3	72.4	58%		40.2	82.9	42%
2013	86.0	119.7	5,322		61.0	97.4	71%		25.0	69.7	29%
2014	124.9	137.6	4,768		73.2	83.9	59%		51.7	102.1	41%
2015	90.2	97.8	5,594		57.3	75.1	63%		33.0	63.6	37%
2016	64.7	77.9	5,512		48.8	61.1	76%		15.8	45.0	24%
2017	69.2	88.4	4,294		47.7	70.8	69%		21.5	51.8	31%
2018	89.5	112.9	5,128		51.7	75.0	58%		37.7	80.7	42%
2019	115.7	132.1	5,467		90.4	125.6	78%		25.2	62.2	22%
2020	67.5	83.6	4,810		44.4	61.9	66%		23.0	58.3	34%

Table 3. Variables tested and included in the final models.

Variables	Comments	Data type	Final model
YEAR	Fishing year	Category	Yes
MONTH	Fishing month	Category	Yes
SEASON	Four seasons	Category	Yes
CDAY	Calendar day	Numeric	Yes
IMP1_HOURS	Corrected trawl hours	Numeric	Yes
SATIG	Swept area rate expressed in M^2/s	Numeric	Yes
LOCAL_TIGER_EFFORT	Effort for the 9 6nm grids centred on the present grid for the 7 days starting 3 days before the present day	Numeric	Yes
nVcode	Number of vessels in the year	Numeric	Yes
ENDEAV	Endeavour prawn catch	Numeric	Yes
MENDV	Blue endeavour prawn catch	Numeric	Yes
MENSI	Red endeavour prawn catch	Numeric	Yes
TIGER	Tiger prawn catch	Numeric	Yes
PESCU	Brown tiger prawn catch	Numeric	Yes
PSEMI	Grooved tiger prawn catch	Numeric	Yes
DEPTH	Fishing depth	Numeric	Yes
LATITUDE	Latitude of the grid with the most catch	Numeric	Yes
LONGITUDE	Longitude of the grid with the most catch	Numeric	Yes
TIGER_REGION	Stock region	Category	Yes
ECHOCOL	Echo-sounder	Category	Yes
HULLG	Hull groups	Category	Yes
NAV_ACCG	Navigation instrument accuracy	Category	Yes
O_BRDN	Use of bycatch reduction device	Category	No
PC_SAT	Personal computer with satellite connection	Category	Yes
PLOTTER	Plotter used	Category	Yes
TRYGEAR	Try gear used	Category	Yes
VCODE	Vessel code	Category	No

Table 4. Annual fishing effort in each of the four Endeavour Prawn Stock Regions.

	Stock 1		Stock 2		Stock 3		Stock 4	
Year	N grid	N boat-day	N grid	N boat-day	N grid	N boat-day	N grid	N boat-day
1970	4	14	56	1651	78	1213	53	858
1971	40	339	65	1687	105	1370	46	546
1972	31	298	57	1224	143	1557	70	947
1973	7	71	60	1492	126	1020	59	695
1974	81	416	55	1038	28	182	36	160
1975	90	716	91	1321	59	427	79	1545
1976	105	1127	86	1523	104	601	104	864
1977	63	423	89	2610	177	1393	128	2118
1978	86	940	123	5476	176	1813	137	2283
1979	110	945	136	3125	309	4549	134	2182
1980	103	1804	119	6222	237	6189	150	4148
1981	111	2830	113	5989	276	6433	127	3647
1982	104	1803	105	4685	325	7514	184	6985
1983	89	1174	127	6320	379	9125	201	5857
1984	103	1466	142	5918	382	7924	191	5426
1985	116	1637	130	4559	381	8677	148	3804
1986	138	2097	145	6588	355	7683	154	3336
1987	107	1509	143	5587	393	10984	102	1206
1988	110	1376	140	5953	416	10559	186	4463
1989	98	1333	147	4858	412	10705	201	6573
1990	97	1870	106	5026	340	10034	171	4758
1991	94	1541	92	3412	325	10266	162	3880
1992	65	974	104	6599	321	7887	165	4336
1993	29	438	88	3047	276	8858	124	2073
1994	51	611	94	4568	267	8545	125	3560
1995	34	453	73	3536	227	5520	134	5642
1996	32	286	81	2718	246	6208	161	5939
1997	44	357	68	2905	228	5092	152	4412
1998	50	739	93	4485	265	7098	128	3239
1999	37	171	97	4358	242	6390	88	968
2000	26	289	94	3586	231	5552	107	2473
2001	43	454	87	2970	239	4657	77	1249
2002	26	441	103	4462	146	2440	57	462
2003	17	86	85	2726	195	4584	23	190
2004	20	98	94	3225	170	3796	7	27
2005	16	82	79	3025	197	3976	35	178
2006	10	32	97	2284	202	4065	34	134
2007	13	98	73	2171	150	2342	20	145
2008	27	519	63	1405	118	1662	46	673
2009	19	90	58	683	150	2953	47	688
2010	12	15	81	1837	180	2435	39	307
2011	34	118	64	879	154	1537	60	1105

	Stock 1		Stock 2		Stock 3		Stock 4	
Year	N grid	N boat-day	N grid	N boat-day	N grid	N boat-day	N grid	N boat-day
2012	50	281	79	1488	156	1810	58	1249
2013	50	322	83	2015	197	2087	73	898
2014	35	340	59	1443	155	1995	49	990
2015	49	400	74	2447	198	2010	69	737
2016	65	712	76	1489	193	2572	68	739
2017	32	218	72	892	184	2527	67	657
2018	64	514	70	1478	184	2381	41	755
2019	51	450	66	782	230	3436	61	799
2020	84	994	62	1209	190	2164	30	443
Mean	58	712	91	3156	224	4643	97	2183

Table 5. Model comparison using combined catch rate of two species of endeavour prawns as a group. GLM: generalised linear model; GAM: generalised additive model; DL: delta-lognormal distribution; Tw: Tweedie distribution; AIC: Akaike information criterion; MSE: mean squared error; R^2: adjusted R-square.

Model	Symbol	Sub-model	AIC	Deviance explained	MSE	R^2
Model 1	GLM-DL1	Binomial	303,580	12.8%		0.128
		Lognormal	1,179,012	36.2%	0.642	0.362
Model 2	GLM-DL2	Binomial	299,806	14.0%		0.140
		Lognormal	1,164,723	38.0%	0.623	0.380
Model 3	GLM-Tw1	Tw	NA	25.1%	0.624	0.251
Model 4	GLM-Tw2	Tw	NA	26.1%	0.605	0.261
Model 5	GAM-DL1	Binomial	289,696	16.9%		0.126
		Lognormal	1,122,694	43.1%	0.572	0.431
Model 6	GAM-DL2	Binomial	287,223	17.6%		0.134
		Lognormal	1,111,902	44.4%	0.560	0.443
Model 7	GAM-Tw1	Tw	5,112,557	44.5%	0.432	0.39
Model 8	GAM-Tw2	Tw	5,098,557	45.8%	0.423	0.404

Table 6. Estimated parameter coefficient for Model 8: GAM-Tw2 for endeavour prawn as a group in all stock regions.

Variable	Estimate	Std. Error	t value	Pr(>|t|)
year1971	-1.56E+00	7.81E-02	-19.948	< 2e-16
year1972	-6.17E-01	6.95E-02	-8.877	< 2e-16
year1973	3.12E-01	6.94E-02	4.495	6.95E-06
year1974	-1.60E+00	1.09E-01	-14.684	< 2e-16
year1975	-8.98E-01	7.98E-02	-11.256	< 2e-16
year1976	-1.01E+00	7.33E-02	-13.814	< 2e-16
year1977	-1.25E+00	7.11E-02	-17.597	< 2e-16
year1978	-4.76E-01	6.00E-02	-7.938	2.06E-15
year1979	-9.30E-01	6.34E-02	-14.664	< 2e-16
year1980	-1.20E+00	5.83E-02	-20.595	< 2e-16
year1981	-1.71E+00	5.95E-02	-28.802	< 2e-16
year1982	-1.50E+00	5.83E-02	-25.652	< 2e-16
year1983	-1.65E+00	5.87E-02	-28.056	< 2e-16
year1984	-2.13E+00	5.91E-02	-36.111	< 2e-16
year1985	-2.21E+00	6.07E-02	-36.381	< 2e-16
year1986	-1.68E+00	6.23E-02	-26.886	< 2e-16
year1987	-1.54E+00	6.66E-02	-23.149	< 2e-16
year1988	-2.34E+00	6.44E-02	-36.308	< 2e-16
year1989	-2.26E+00	6.40E-02	-35.316	< 2e-16
year1990	-2.25E+00	6.17E-02	-36.476	< 2e-16
year1991	-1.67E+00	6.33E-02	-26.385	< 2e-16
year1992	-1.42E+00	6.08E-02	-23.432	< 2e-16
year1993	-1.48E+00	6.34E-02	-23.308	< 2e-16
year1994	-1.29E+00	5.98E-02	-21.5	< 2e-16
year1995	-2.50E+00	6.18E-02	-40.534	< 2e-16
year1996	-1.15E+00	6.06E-02	-18.916	< 2e-16
year1997	-1.67E+00	6.18E-02	-27.068	< 2e-16
year1998	-1.44E+00	6.08E-02	-23.772	< 2e-16
year1999	-7.44E-01	6.44E-02	-11.538	< 2e-16
year2000	-1.14E+00	6.22E-02	-18.271	< 2e-16
year2001	-2.76E+00	6.94E-02	-39.675	< 2e-16
year2002	-1.12E+00	7.55E-02	-14.829	< 2e-16
year2003	-1.33E+00	8.78E-02	-15.129	< 2e-16
year2004	-3.30E+00	1.22E-01	-27.156	< 2e-16
year2005	-1.53E+00	9.68E-02	-15.791	< 2e-16
year2006	-8.73E-01	1.01E-01	-8.682	< 2e-16
year2007	-1.89E+00	1.12E-01	-16.855	< 2e-16
year2008	-1.71E+00	1.09E-01	-15.697	< 2e-16
year2009	-2.49E+00	1.01E-01	-24.645	< 2e-16
year2010	-1.99E+00	9.72E-02	-20.496	< 2e-16
year2011	-2.61E+00	1.12E-01	-23.363	< 2e-16
year2012	-1.81E+00	9.05E-02	-19.968	< 2e-16
year2013	-1.22E+00	8.11E-02	-15.018	< 2e-16
year2014	-1.93E+00	8.87E-02	-21.759	< 2e-16

Variable	Estimate	Std. Error	t value	Pr(>|t|)
year2015	-1.53E+00	8.55E-02	-17.926	< 2e-16
year2016	-2.13E+00	8.76E-02	-24.297	< 2e-16
year2017	-9.61E-01	1.02E-01	-9.402	< 2e-16
year2018	-9.20E-01	9.15E-02	-10.063	< 2e-16
year2019	6.28E-01	8.38E-02	7.499	6.45E-14
year2020	-1.24E+00	9.80E-02	-12.608	< 2e-16
cday	-1.24E-02	1.25E-02	-0.988	0.323068
tiger_region4	9.24E+00	3.39E+00	2.73	0.006329
tiger_region5	8.49E+00	3.39E+00	2.508	0.012156
tiger_region6	8.80E+00	3.39E+00	2.6	0.009317
tiger_region7	1.10E+01	3.37E+00	3.272	0.001068
month4	1.18E-01	3.85E-02	3.056	0.00224
month5	1.17E-01	4.31E-02	2.724	0.006449
month8	-1.29E+00	1.41E-01	-9.169	< 2e-16
month9	-1.31E+00	1.39E-01	-9.434	< 2e-16
month10	-1.32E+00	1.39E-01	-9.499	< 2e-16
month11	-1.31E+00	1.40E-01	-9.381	< 2e-16
trygear1	1.66E-01	5.94E-03	28.027	< 2e-16
Plotter1	3.13E-02	9.05E-03	3.454	0.000552
pc_sat1	4.35E-02	6.34E-03	6.853	7.25E-12
echocol1	-2.33E-02	5.21E-03	-4.467	7.93E-06
hullg2	6.26E-02	4.04E-03	15.492	< 2e-16
hullg3	1.18E-01	5.16E-03	22.897	< 2e-16
hullg4	1.03E-01	6.29E-03	16.45	< 2e-16
hullg9	1.75E-01	4.58E-02	3.812	0.000138
navaccmetres20	-4.83E-02	4.73E-03	-10.221	< 2e-16
navaccmetres120	-5.58E-02	8.86E-03	-6.303	2.91E-10
navaccmetres500	-1.15E-01	1.37E-02	-8.365	< 2e-16
navaccmetres10000	-1.46E-01	1.45E-02	-10.088	< 2e-16
navaccmetres48000	1.59E-02	1.97E-02	0.808	0.419058
1971:cday	3.95E-03	2.91E-04	13.563	< 2e-16
1972:cday	-3.91E-04	2.64E-04	-1.482	0.138348
1973:cday	-2.51E-03	2.67E-04	-9.398	< 2e-16
1974:cday	6.39E-03	3.93E-04	16.282	< 2e-16
1975:cday	9.47E-04	3.03E-04	3.13	0.001747
1976:cday	2.60E-03	2.75E-04	9.449	< 2e-16
1977:cday	4.23E-03	2.66E-04	15.901	< 2e-16
1978:cday	-4.78E-04	2.29E-04	-2.088	0.036782
1979:cday	1.78E-03	2.41E-04	7.369	1.72E-13
1980:cday	1.64E-03	2.21E-04	7.392	1.44E-13
1981:cday	3.31E-03	2.24E-04	14.753	< 2e-16
1982:cday	2.44E-03	2.19E-04	11.172	< 2e-16
1983:cday	1.02E-03	2.22E-04	4.605	4.13E-06
1984:cday	4.10E-03	2.22E-04	18.516	< 2e-16
1985:cday	5.48E-03	2.28E-04	24.065	< 2e-16
1986:cday	-3.31E-04	2.34E-04	-1.415	0.157213

Variable	Estimate	Std. Error	t value	Pr(>|t|)
1987:cday	9.67E-05	2.54E-04	0.381	0.703262
1988:cday	2.16E-03	2.42E-04	8.94	< 2e-16
1989:cday	2.52E-03	2.38E-04	10.579	< 2e-16
1990:cday	1.95E-03	2.30E-04	8.46	< 2e-16
1991:cday	8.52E-04	2.37E-04	3.587	0.000334
1992:cday	-1.68E-04	2.25E-04	-0.746	0.455855
1993:cday	9.52E-04	2.39E-04	3.98	6.89E-05
1994:cday	2.56E-04	2.22E-04	1.154	0.248545
1995:cday	5.64E-03	2.28E-04	24.713	< 2e-16
1996:cday	6.56E-04	2.26E-04	2.91	0.003613
1997:cday	3.63E-03	2.33E-04	15.556	< 2e-16
1998:cday	2.34E-03	2.26E-04	10.332	< 2e-16
1999:cday	-1.96E-04	2.46E-04	-0.799	0.424206
2000:cday	1.60E-03	2.32E-04	6.896	5.37E-12
2001:cday	9.22E-03	2.60E-04	35.523	< 2e-16
2002:cday	6.44E-04	2.74E-04	2.352	0.018669
2003:cday	1.69E-03	3.13E-04	5.396	6.82E-08
2004:cday	8.19E-03	4.18E-04	19.578	< 2e-16
2005:cday	7.57E-04	3.66E-04	2.072	0.038307
2006:cday	-9.53E-05	3.78E-04	-0.252	0.800748
2007:cday	2.15E-03	4.14E-04	5.209	1.90E-07
2008:cday	1.16E-03	3.99E-04	2.913	0.003574
2009:cday	5.74E-03	3.66E-04	15.661	< 2e-16
2010:cday	5.01E-03	3.50E-04	14.307	< 2e-16
2011:cday	6.96E-03	4.14E-04	16.798	< 2e-16
2012:cday	3.76E-03	3.29E-04	11.433	< 2e-16
2013:cday	1.53E-03	3.00E-04	5.082	3.74E-07
2014:cday	5.11E-03	3.24E-04	15.793	< 2e-16
2015:cday	2.93E-03	3.12E-04	9.404	< 2e-16
2016:cday	3.83E-03	3.26E-04	11.758	< 2e-16
2017:cday	-5.15E-04	3.81E-04	-1.354	0.175823
2018:cday	4.19E-05	3.38E-04	0.124	0.901416
2019:cday	-4.89E-03	3.10E-04	-15.775	< 2e-16
2020:cday	1.77E-06	3.65E-04	0.005	0.996134
tiger_regio4:cday	1.45E-03	9.74E-05	14.884	< 2e-16
tiger_regio5:cday	2.79E-03	9.61E-05	29.033	< 2e-16
tiger_regio6:cday	1.50E-03	1.17E-04	12.797	< 2e-16
tiger_regio7:cday	4.59E-03	1.35E-04	34.042	< 2e-16

Table 7. Approximate significance of smooth terms for Model 8: GAM-Tw2 on two species of endeavour prawn as a group.

Variable	edf	Ref.df	F	p-value
te(lon,lat)	74.08	75.473	822.34	<2e-16
s(depth)	8.945	8.999	397.55	<2e-16
s(imp1_hours)	8.733	8.973	2473.07	<2e-16
s(satig)	8.525	8.936	864.49	<2e-16
s(prob_semi)	8.967	9	2276.07	<2e-16
s(local_tiger_effort)	7.96	8.54	539.02	<2e-16
s(nVcode)	8.812	8.99	74.72	<2e-16
s(cday)	8.963	8.999	534.07	<2e-16

Table 8. Standardized abundance index (SI_y), its standard deviation (SD[SI_y]), and relative fishing power (FP_y) from Model 8, GAM-Tw2 for two species of endeavour prawns as a group from 1970 to 2020. Nominal catch rate scaled to a mean around 1 is included as a comparison.

Year	Nominal index	SI_y	SD[SI_y]	FP_y
1970	1.20	2.32	0.20	1.00
1971	0.82	1.38	0.12	1.15
1972	0.74	1.10	0.10	1.29
1973	1.01	1.60	0.14	1.22
1974	2.22	2.64	0.22	1.62
1975	1.18	1.19	0.10	1.91
1976	1.79	1.67	0.14	2.07
1977	1.60	2.04	0.17	1.51
1978	0.97	1.24	0.10	1.51
1979	1.21	1.45	0.12	1.61
1980	1.01	1.05	0.08	1.85
1981	1.02	0.98	0.08	2.01
1982	0.99	0.97	0.08	1.98
1983	0.55	0.56	0.05	1.90
1984	0.74	0.79	0.06	1.79
1985	1.03	1.08	0.09	1.84
1986	0.41	0.38	0.03	2.09
1987	0.41	0.49	0.04	1.63
1988	0.35	0.38	0.03	1.77
1989	0.50	0.46	0.04	2.13
1990	0.40	0.39	0.03	1.97
1991	0.63	0.52	0.04	2.31
1992	0.59	0.51	0.04	2.21
1993	0.66	0.66	0.05	1.95
1994	0.70	0.66	0.05	2.03
1995	0.95	0.83	0.06	2.22
1996	1.14	0.85	0.07	2.59
1997	1.33	1.12	0.09	2.29
1998	1.11	0.99	0.08	2.17
1999	0.97	1.01	0.08	1.84
2000	1.13	1.11	0.09	1.96
2001	1.57	1.72	0.14	1.76
2002	0.71	0.87	0.07	1.57
2003	0.77	0.93	0.08	1.60
2004	0.71	0.74	0.06	1.85
2005	0.49	0.59	0.05	1.59
2006	0.74	0.91	0.08	1.57
2007	0.56	0.60	0.05	1.80
2008	0.66	0.55	0.05	2.32
2009	0.98	0.86	0.07	2.20
2010	1.27	1.18	0.10	2.07

Year	Nominal index	SI_y	SD[SI_y]	FP_y
2011	1.37	1.07	0.09	2.46
2012	1.41	1.01	0.08	2.68
2013	1.27	1.00	0.08	2.44
2014	1.84	1.30	0.11	2.74
2015	1.33	1.07	0.09	2.40
2016	0.95	0.74	0.06	2.48
2017	1.02	0.75	0.06	2.64
2018	1.32	0.90	0.08	2.82
2019	1.71	1.14	0.10	2.88
2020	0.99	0.65	0.06	2.96

Table 9. Comparison of generalized additive models (GAM) on modelling catch rate of blue and red endeavour prawns. DL: delta-lognormal distribution; Tw: Tweedie distribution; AIC: Akaike information criterion; MSE: mean squared error; R^2: adjusted R-square.

Model	Symbol	Sub-model	AIC	Deviance explained	MSE	R^2
Blue endeavour						
Model 5	GAM-DL1	Binomial	289,696	16.9%		0.126
		Lognormal	1,149,444	55.1%	0.604	0.551
Model 6	GAM-DL2	Binomial	287,223	17.6%		0.134
		Lognormal	1,135,956	56.4%	0.588	0.563
Model 7	GAM-Tw1	Tw	4,733,519	48.2%	0.470	0.412
Model 8	GAM-Tw2	Tw	4,717,655	49.6%	0.457	0.430
Red endeavour						
Model 5	GAM-DL1	Binomial	289,696	16.9%		0.126
		Lognormal	1,330,558	91.2%	0.873	0.912
Model 6	GAM-DL2	Binomial	287,223	17.6%		0.134
		Lognormal	1,317,002	91.5%	0.849	0.915
Model 7	GAM-Tw1	Tw	2,314,420	78.1%	1.072	-0.469
Model 8	GAM-Tw2	Tw	2,299,781	78.7%	1.030	0.284

Table 10. Comparison of generalized additive models (GAM) for modelling catch rate of two endeavour prawn species as a group in each of the four Endeavour Prawn Stock Regions. DL: delta-lognormal distribution; Tw: Tweedie distribution; AIC: Akaike information criterion; MSE: mean squared error; R^2: adjusted R-square.

Stock	Model	Symbol	Sub-model	AIC	Deviance explained	MSE	R^2
1	Model5	GAM-DL1	Binomial	13,057	31.3%		0.234
			Lognormal	71,105	63.0%	0.478	0.628
	Model6	GAM-DL2	Binomial	12,973	32.2%		0.242
			Lognormal	69,817	64.5%	0.459	0.642
	Model7	GAM-Tw1	Tw	381,029	57.1%	0.491	0.481
	Model8	GAM-Tw2	Tw	379,412	59.0%	0.474	0.504
2	Model5	GAM-DL1	Binomial	93,796	15.4%		0.12
			Lognormal	314,112	37.0%	0.521	0.369
	Model6	GAM-DL2	Binomial	92,971	16.2%		0.128
			Lognormal	311,119	38.3%	0.510	0.382
	Model7	GAM-Tw1	Tw	1,411,415	39.0%	0.575	0.342
	Model8	GAM-Tw2	Tw	1,407,248	40.4%	0.563	0.361
3	Model5	GAM-DL1	Binomial	134,461	16.4%		0.123
			Lognormal	464,284	42.6%	0.525	0.426
	Model6	GAM-DL2	Binomial	132,912	17.4%		0.133
			Lognormal	456,954	44.6%	0.506	0.445
	Model7	GAM-Tw1	Tw	2,132,139	45.0%	0.570	0.406
	Model8	GAM-Tw2	Tw	2,120,568	47.6%	0.550	0.453
4	Model5	GAM-DL1	Binomial	38,416	32.8%		0.278
			Lognormal	230,088	40.8%	0.539	0.407
	Model6	GAM-DL2	Binomial	38,192	33.3%		0.282
			Lognormal	224,103	44.2%	0.508	0.441
	Model7	GAM-Tw1	Tw	1,120,541	43.5%	0.490	0.405
	Model8	GAM-Tw2	Tw	1,114,215	46.4%	0.468	0.438

Table 11. Standardized abundance index (SI_y), its standard deviation (SD[SI_y]), and fishing power (FP_y) from Model 6, GAM-DL2 for two species of endeavour prawns as a group in each Endeavour Prawn Stock Region from 1970 to 2020.

	stock 1			Stock 2			Stock 3			Stock 4		
Year	SI_y	SD[SI_y]	FP_y	SI_y	SD[SI_y]	FP_y	SI_y	SD[SI_y]	FP_y	SI_y	SD[SI_y]	FP_y
1970	0.66	0.16	1.00	3.00	0.75	1.00	2.45	0.33	1.00	1.42	0.34	1.00
1971	0.85	0.16	2.69	1.82	0.50	1.31	1.12	0.16	0.99	1.56	0.34	0.65
1972	0.81	0.25	2.79	1.51	0.41	1.29	0.75	0.10	1.42	1.61	0.37	0.53
1973	2.35	0.36	1.18	2.36	0.57	1.18	1.38	0.17	1.73	1.68	0.43	0.46
1974	1.12	0.16	5.70	3.62	0.87	1.44	1.62	0.26	1.69	2.44	0.60	0.35
1975	1.19	0.14	3.09	1.23	0.31	1.87	0.98	0.17	1.98	1.47	0.28	0.61
1976	0.83	0.24	7.03	1.44	0.35	1.91	0.93	0.15	2.01	1.63	0.31	0.66
1977	0.92	0.14	6.20	2.01	0.49	1.77	1.88	0.23	1.47	1.04	0.17	1.57
1978	0.90	0.09	4.15	0.97	0.25	2.06	1.09	0.13	1.60	1.24	0.21	0.83
1979	1.77	0.15	2.45	1.21	0.30	1.83	1.62	0.18	1.32	1.21	0.20	1.09
1980	1.06	0.11	3.23	1.09	0.26	1.89	1.22	0.14	1.68	0.86	0.14	0.98
1981	1.42	0.16	2.54	0.95	0.23	1.99	1.03	0.12	1.48	0.92	0.15	1.04
1982	1.54	0.15	2.87	0.70	0.18	2.17	0.96	0.11	1.73	0.93	0.15	0.97
1983	1.09	0.10	2.05	0.51	0.13	1.97	0.60	0.07	1.60	0.60	0.10	1.09
1984	0.86	0.07	2.93	0.64	0.16	2.25	0.93	0.11	1.50	0.72	0.12	1.05
1985	1.13	0.11	2.14	1.05	0.25	2.24	1.38	0.15	1.49	0.73	0.12	1.37
1986	0.80	0.07	2.39	0.30	0.10	2.21	0.47	0.06	1.47	0.41	0.07	0.91
1987	0.81	0.08	2.11	0.50	0.15	1.99	0.41	0.06	1.46	0.82	0.14	1.02
1988	0.80	0.07	1.79	0.32	0.10	1.93	0.41	0.05	1.51	0.46	0.08	0.92
1989	0.95	0.11	1.72	0.27	0.09	2.37	0.41	0.05	1.81	0.64	0.11	1.14
1990	0.80	0.07	1.32	0.32	0.09	2.05	0.42	0.05	1.77	0.48	0.08	1.04
1991	1.25	0.11	1.50	0.49	0.13	1.83	0.49	0.06	2.09	0.62	0.10	1.49
1992	0.57	0.08	0.89	0.50	0.13	1.90	0.61	0.07	2.10	0.68	0.11	1.29
1993	0.59	0.07	0.74	0.57	0.15	2.19	0.71	0.08	1.79	0.83	0.14	1.38
1994	0.87	0.08	1.00	0.72	0.19	2.51	0.51	0.06	2.41	0.61	0.10	1.54
1995	0.90	0.09	2.76	0.77	0.19	2.26	0.95	0.10	1.70	0.74	0.12	1.56
1996	0.57	0.07	2.33	0.68	0.17	2.25	0.86	0.09	2.19	0.95	0.15	1.57
1997	1.07	0.12	5.96	1.11	0.27	1.98	0.95	0.11	2.06	1.21	0.20	1.42
1998	0.59	0.11	3.42	1.20	0.29	2.53	1.02	0.11	1.83	0.82	0.14	1.79
1999	0.65	0.13	3.52	1.27	0.30	2.06	0.89	0.10	2.22	0.68	0.12	1.62
2000	1.22	0.17	1.21	1.05	0.25	1.99	1.49	0.16	1.49	1.03	0.17	1.62
2001	0.61	0.09	6.93	1.58	0.38	2.64	2.06	0.23	1.47	1.17	0.20	1.40
2002	0.53	0.15	2.13	0.80	0.20	1.94	1.34	0.15	1.39	0.87	0.17	1.37
2003	0.46	0.13	3.76	0.98	0.24	2.26	1.02	0.12	1.51	0.59	0.17	2.28
2004	0.38	0.12	2.55	0.68	0.19	2.71	1.00	0.12	1.60	0.63	0.38	1.81
2005	0.34	0.09	1.32	0.53	0.17	2.17	0.76	0.09	1.48	0.77	0.17	1.12
2006	1.88	0.35	0.27	0.89	0.25	2.22	0.94	0.11	1.73	0.73	0.19	0.96
2007	0.88	0.24	0.26	0.51	0.18	2.36	0.77	0.10	1.86	0.40	0.08	1.76
2008	1.00	0.13	0.92	0.58	0.19	2.23	0.60	0.08	1.65	0.79	0.14	1.84
2009	0.76	0.20	2.22	0.81	0.25	3.35	0.99	0.12	1.48	1.02	0.18	1.93
2010	0.21	0.19	1.61	1.04	0.32	2.87	1.30	0.16	2.10	1.41	0.28	1.48
2011	0.71	0.75	5.92	1.20	0.32	2.84	0.97	0.12	1.99	0.99	0.18	1.81

	stock 1			Stock 2			Stock 3			Stock 4		
Year	SI_y	SD[SI_y]	FP_y	SI_y	SD[SI_y]	FP_y	SI_y	SD[SI_y]	FP_y	SI_y	SD[SI_y]	FP_y
2012	1.45	0.36	1.40	0.83	0.25	2.36	1.12	0.14	1.65	1.19	0.21	2.30
2013	1.79	0.26	2.08	0.85	0.23	2.19	1.02	0.12	2.05	1.39	0.25	1.84
2014	2.69	0.44	1.92	1.18	0.31	2.95	1.02	0.12	2.49	1.29	0.23	2.43
2015	1.20	0.16	4.00	1.11	0.32	2.68	0.94	0.12	2.39	1.20	0.22	1.53
2016	1.10	0.15	1.96	0.67	0.21	2.62	0.94	0.11	2.01	0.69	0.13	1.74
2017	0.52	0.11	1.93	0.59	0.20	2.58	0.76	0.09	2.70	0.89	0.19	1.95
2018	1.48	0.24	2.97	0.93	0.26	2.60	0.73	0.09	2.53	1.28	0.25	1.78
2019	1.07	0.18	2.83	0.76	0.24	2.98	1.23	0.15	2.54	1.62	0.30	1.80
2020	1.02	0.19	2.57	0.29	0.15	3.84	0.93	0.11	1.96	1.01	0.20	1.39

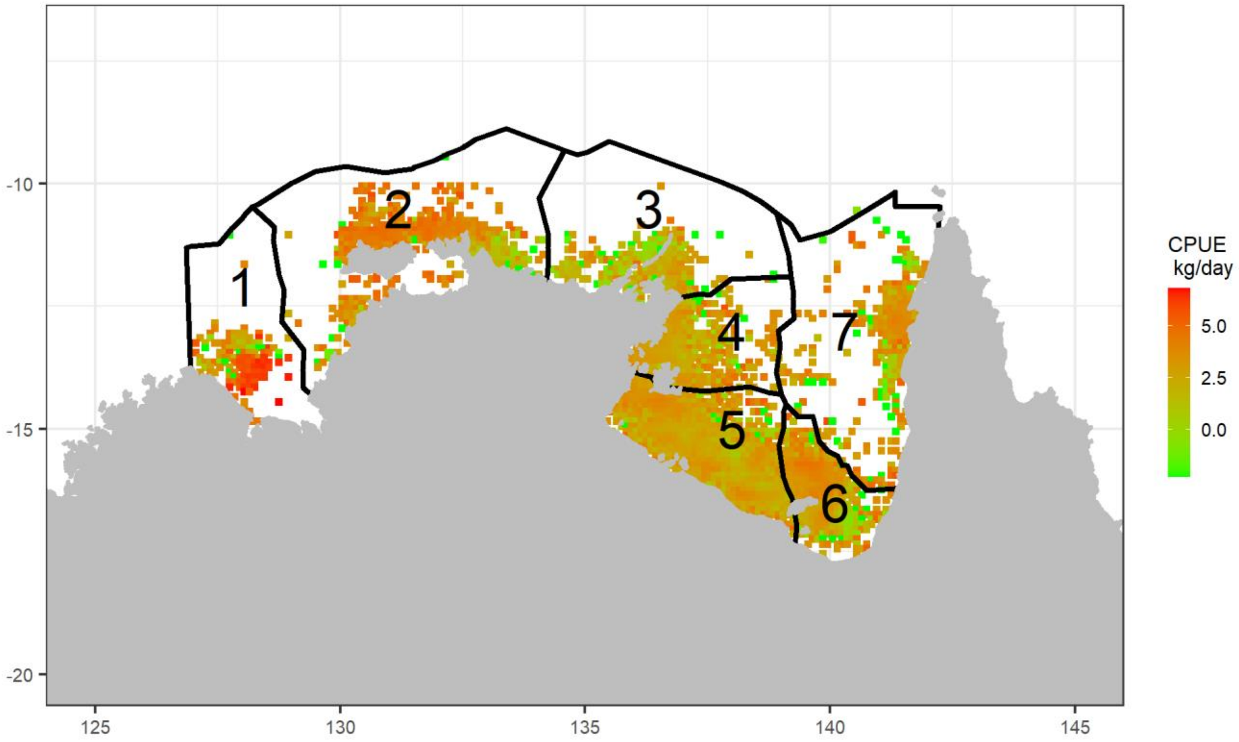
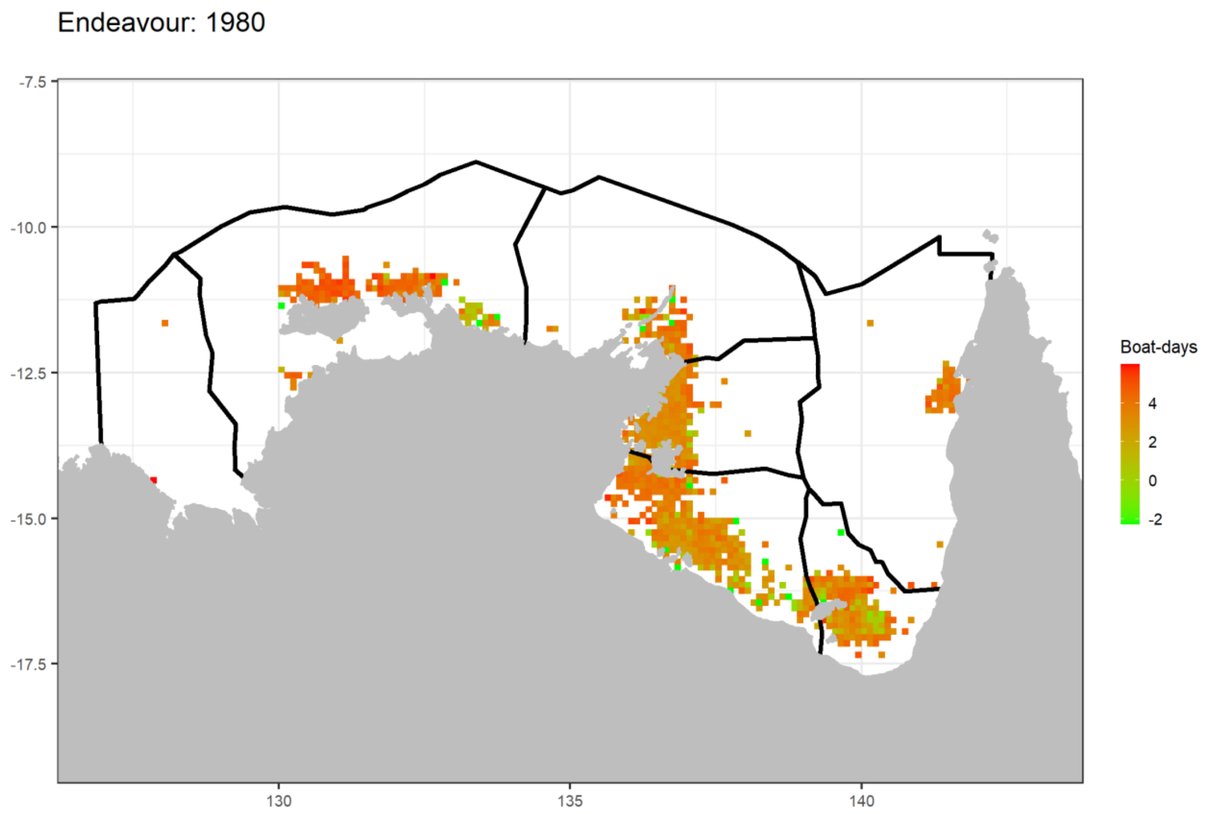


Figure 1. Spatial distribution of average endeavour prawns catch per boat-day (log scale) in NPF logbooks from 1970 to 2020. The black lines divide NPF into seven tiger prawn stock regions. See Figure 9 for a description of the four endeavour assessment regions (i.e., Endeavour Prawn Stock 1 = Tiger Prawn Stocks 1, 2, 3; Endeavour Prawn Stock 2 = Tiger Prawn Stock 4; Endeavour Prawn Stock 3 = Tiger Prawn Stock 5; Endeavour Prawn Stock 4 = Tiger Prawn Stocks 6, 7).



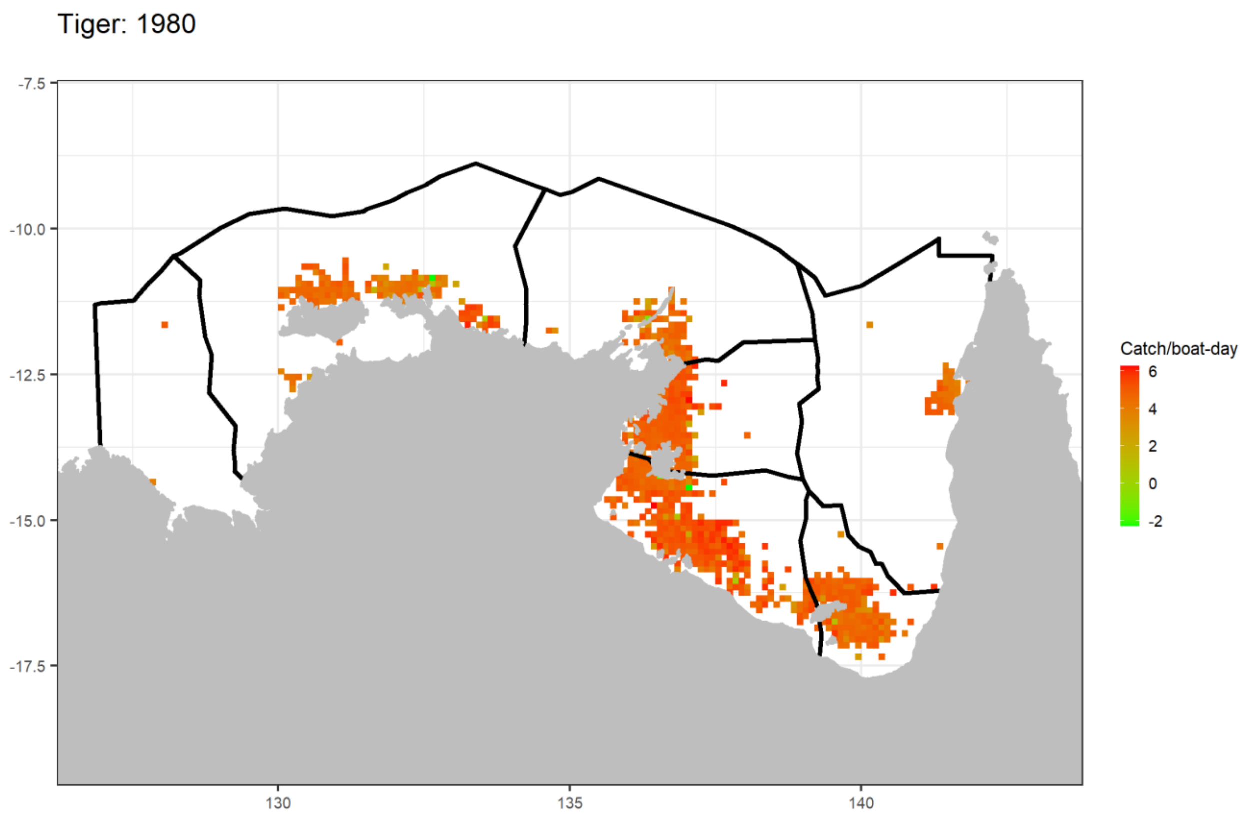


Figure 2. Catch distribution (log scale) comparison between tiger prawns and endeavour prawns in 1980.

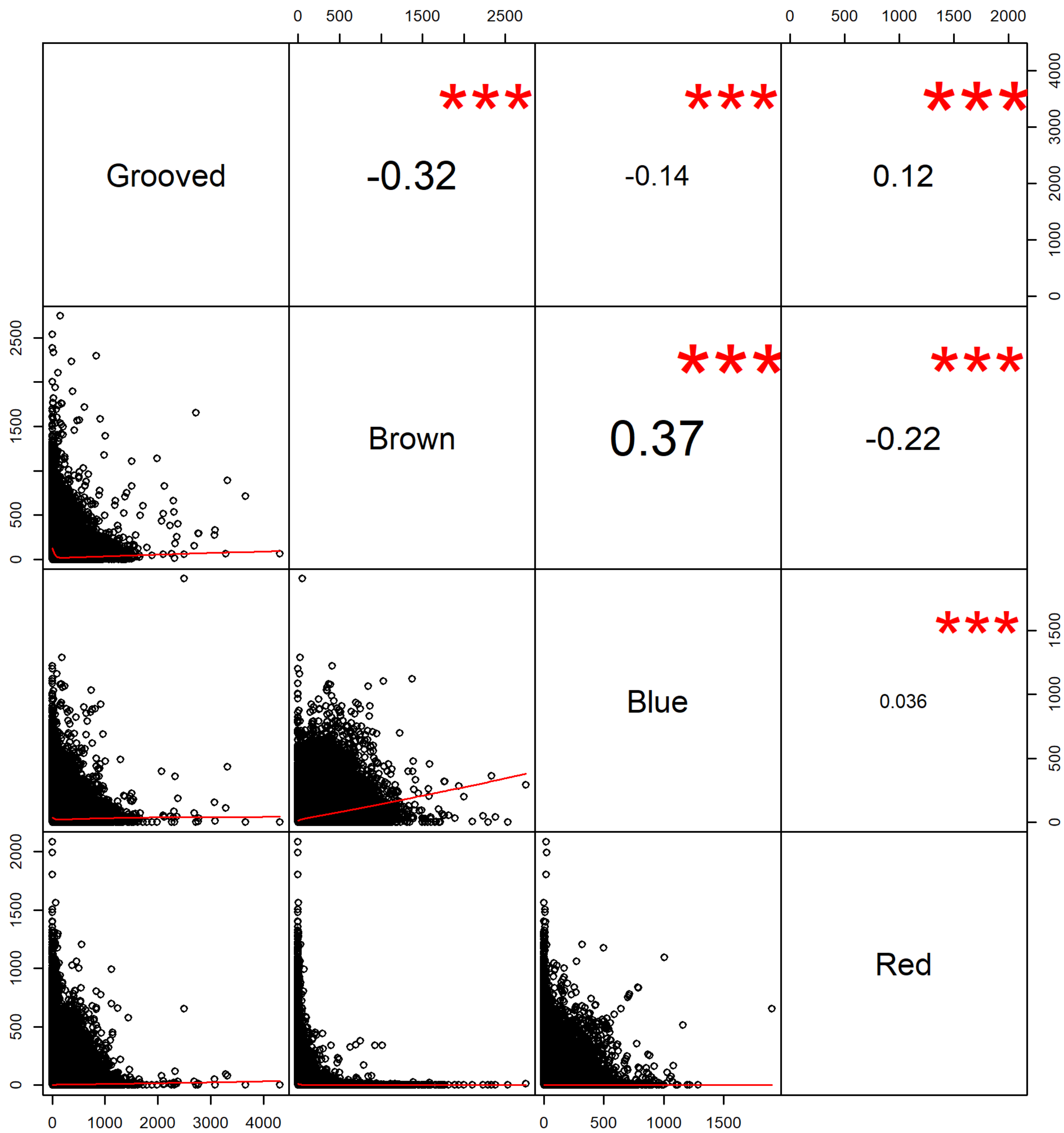


Figure 3. Catch correlation between grooved tiger prawn, brown tiger prawn, blue endeavour prawn, and red endeavour prawn. The values are Pearson correlation coefficient and the red stars are significant levels.

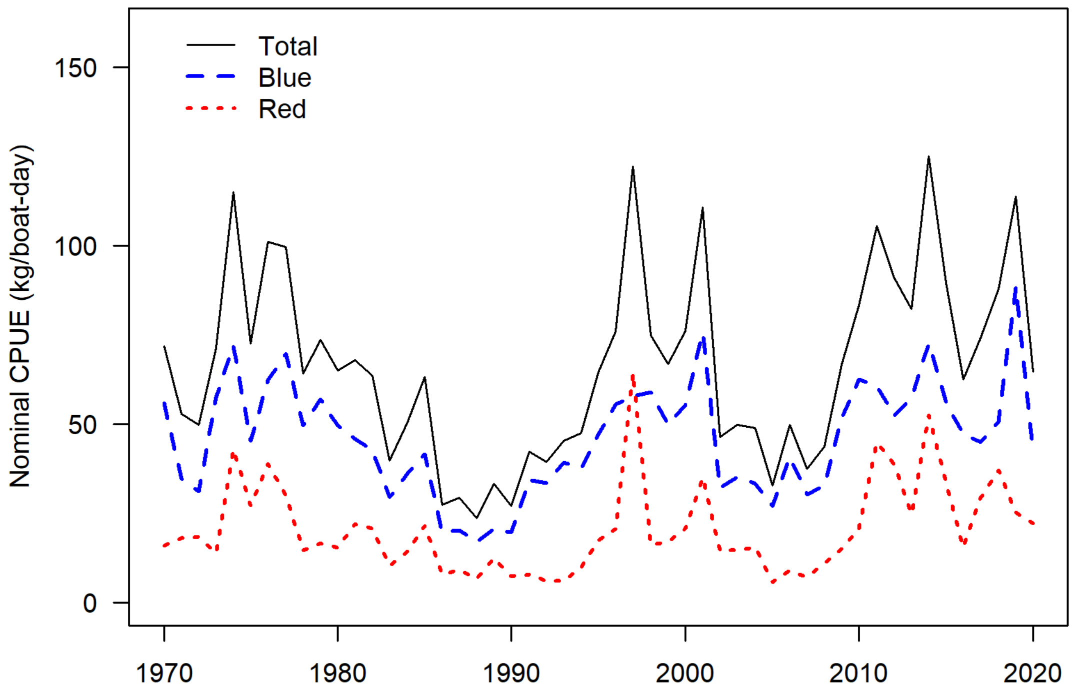


Figure 4. Nominal CPUE (kg/boat-day) for the two species of endeavour prawns from 1970 to 2020.

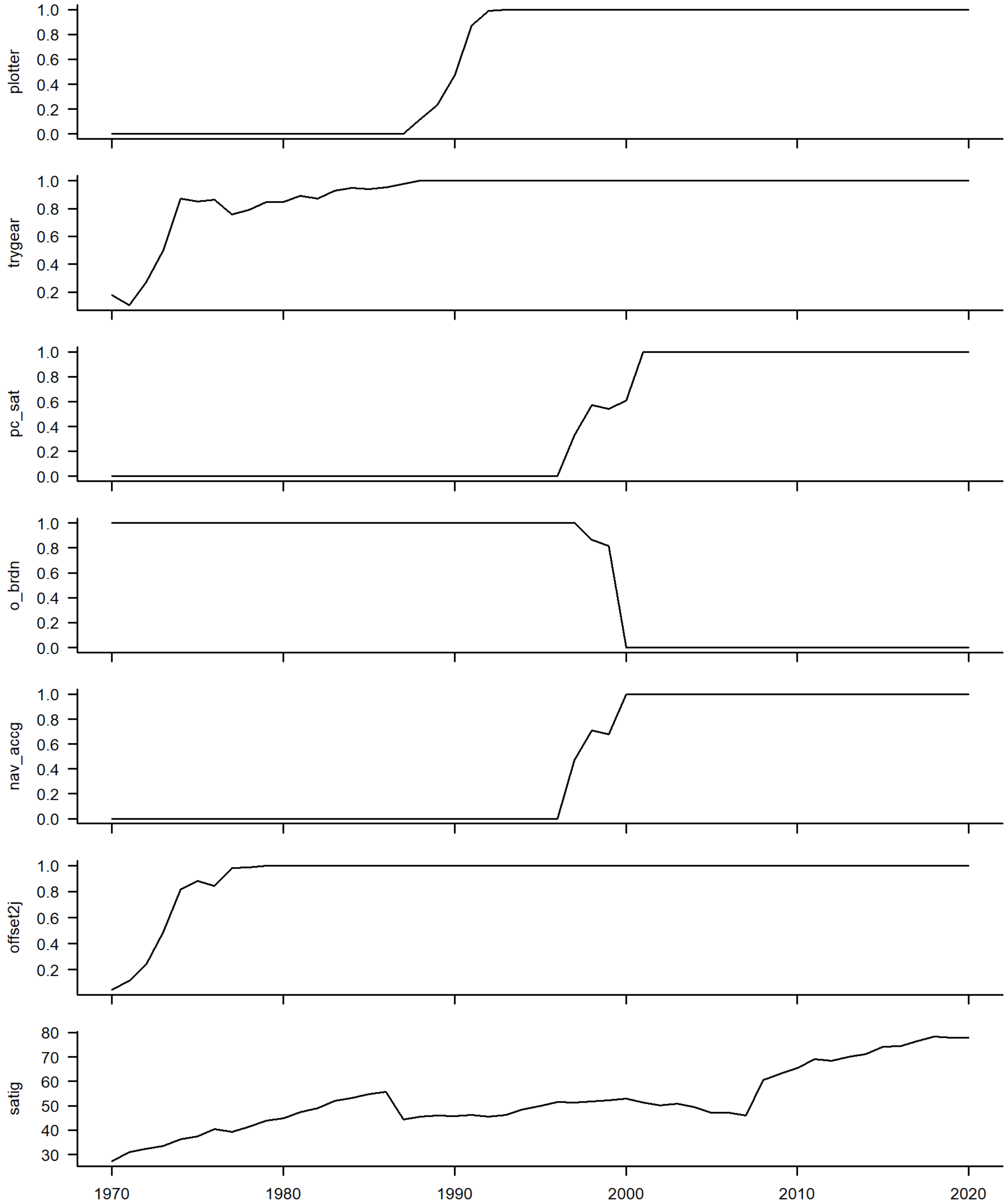


Figure 5. Example of adopting techologies by tiger prawn fleet in the NPF. Offset2j was estimated for tiger prawn fishing power analysis and was not used for endeavour prawn CPUE modeling.

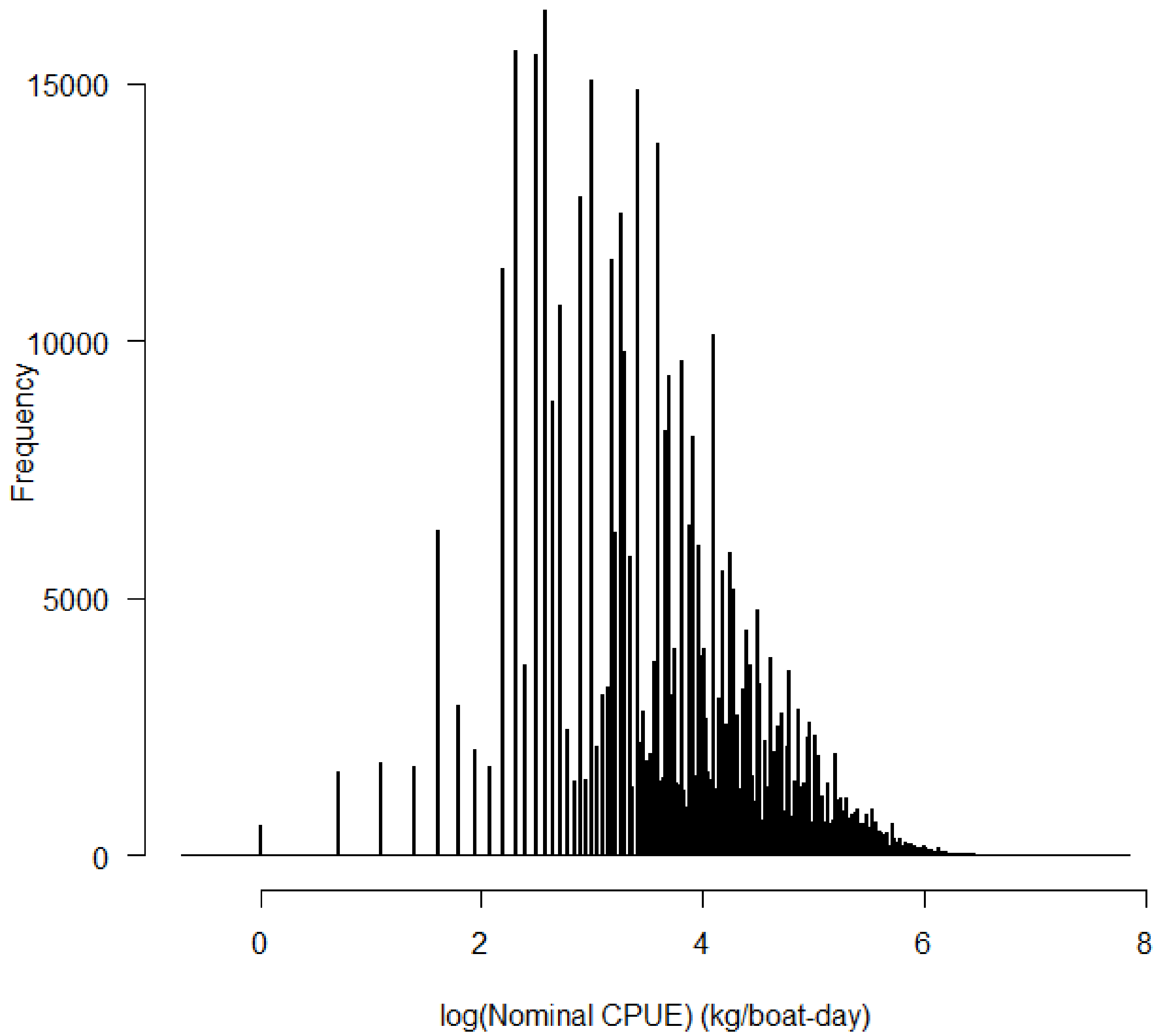


Figure 6. Frequency distribution of log-scale non-zero catch records of endeavour prawns in NPF logbooks aggregated from 1970 to 2020.

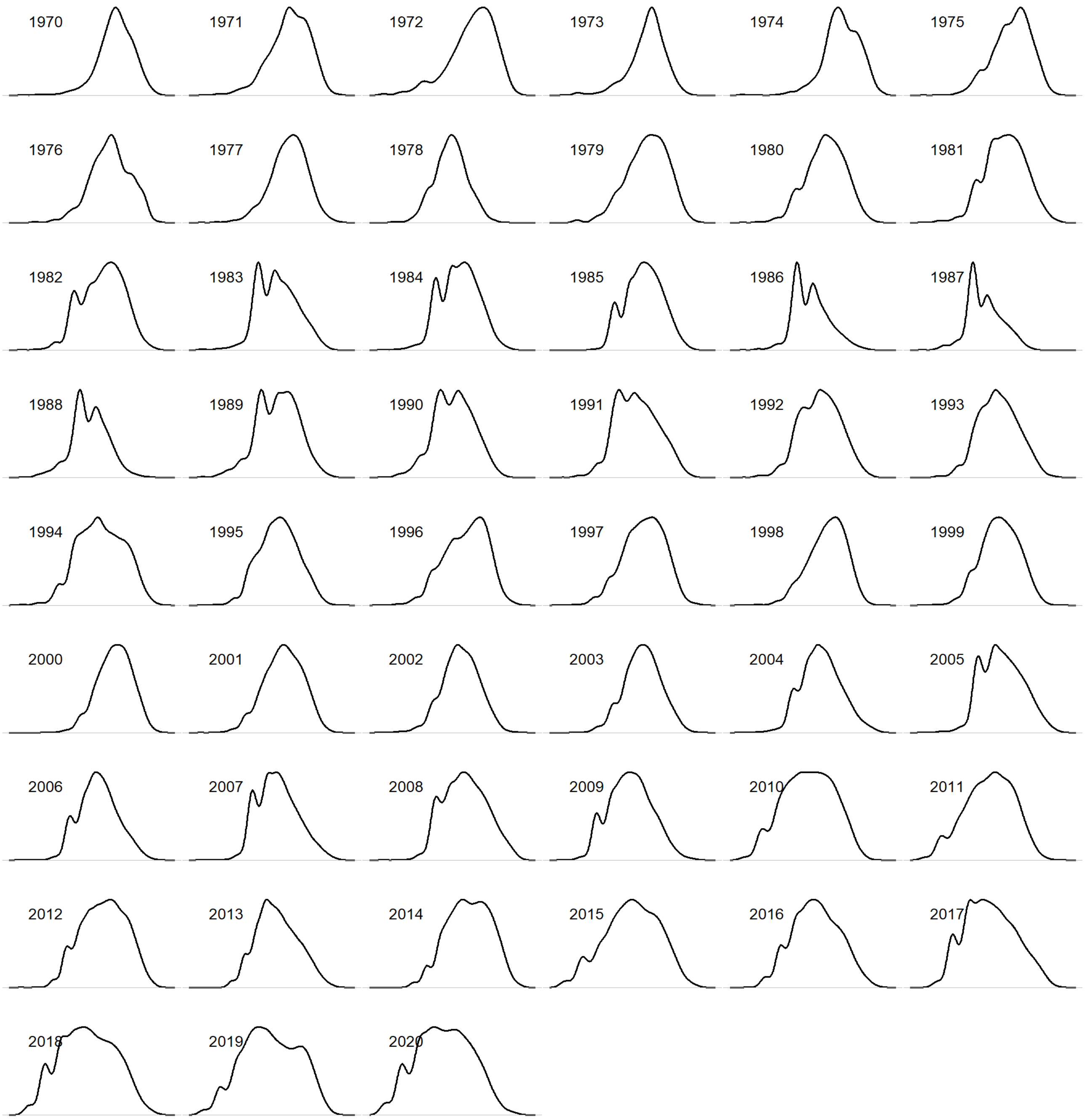


Figure 7. Frequency distribution of log-scale annual non-zero catch records of endeavour prawns in NPF logbooks from 1970 to 2020.

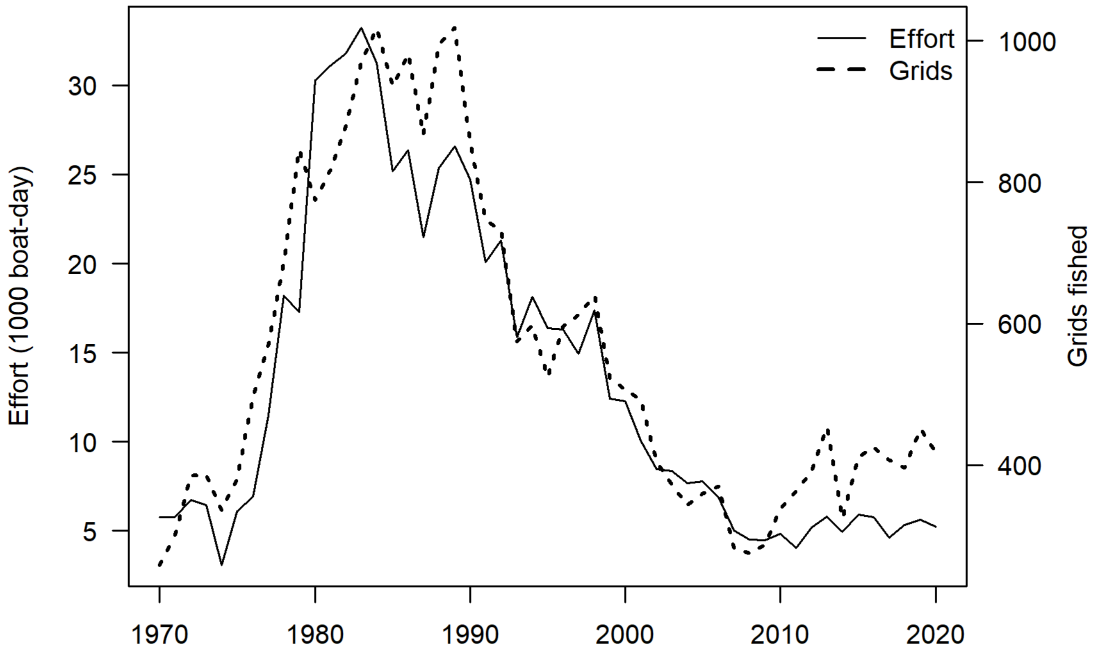


Figure 8. Fishing effort and the number of grids (0.1 by 0.1 degree) fished from 1970 to 2020.

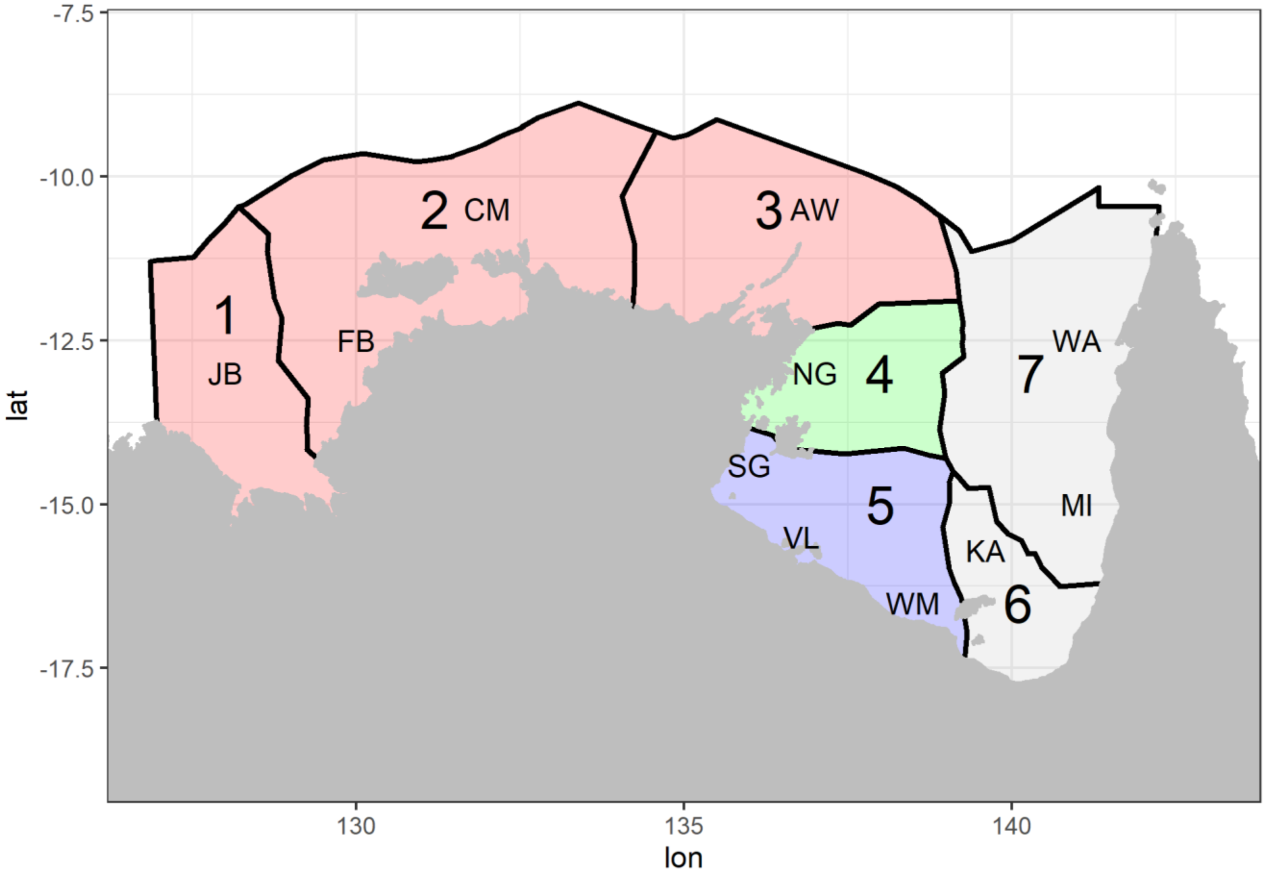


Figure 9. Seven Tiger Stock Region and four Endeavour Prawn Stock Regions (identified by colour) in the NPF.

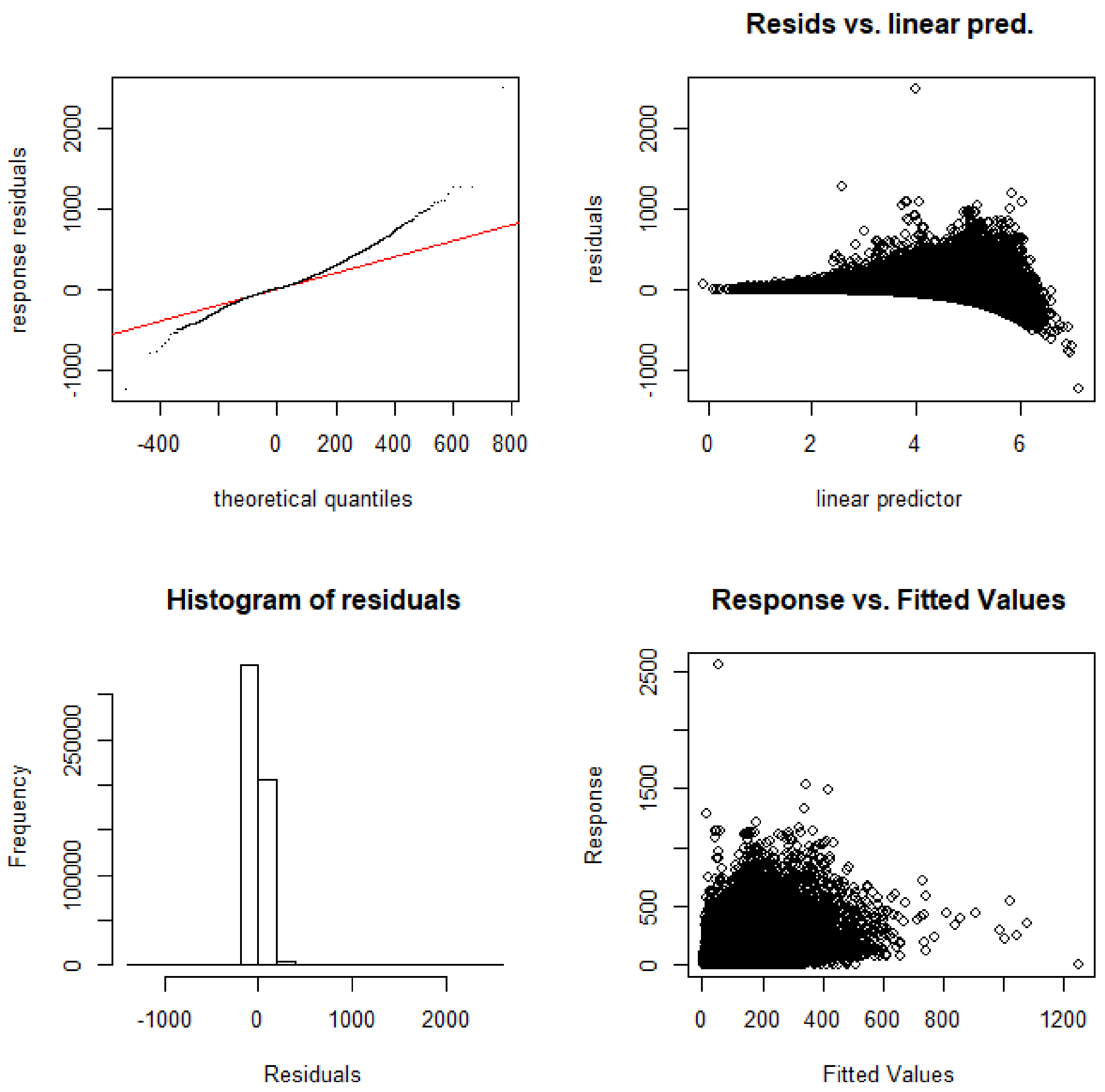


Figure 10. Model diagnostics about the fitting procedure and results of Model 8, GAM-Tw2, for the two endeavour prawn species as a group.

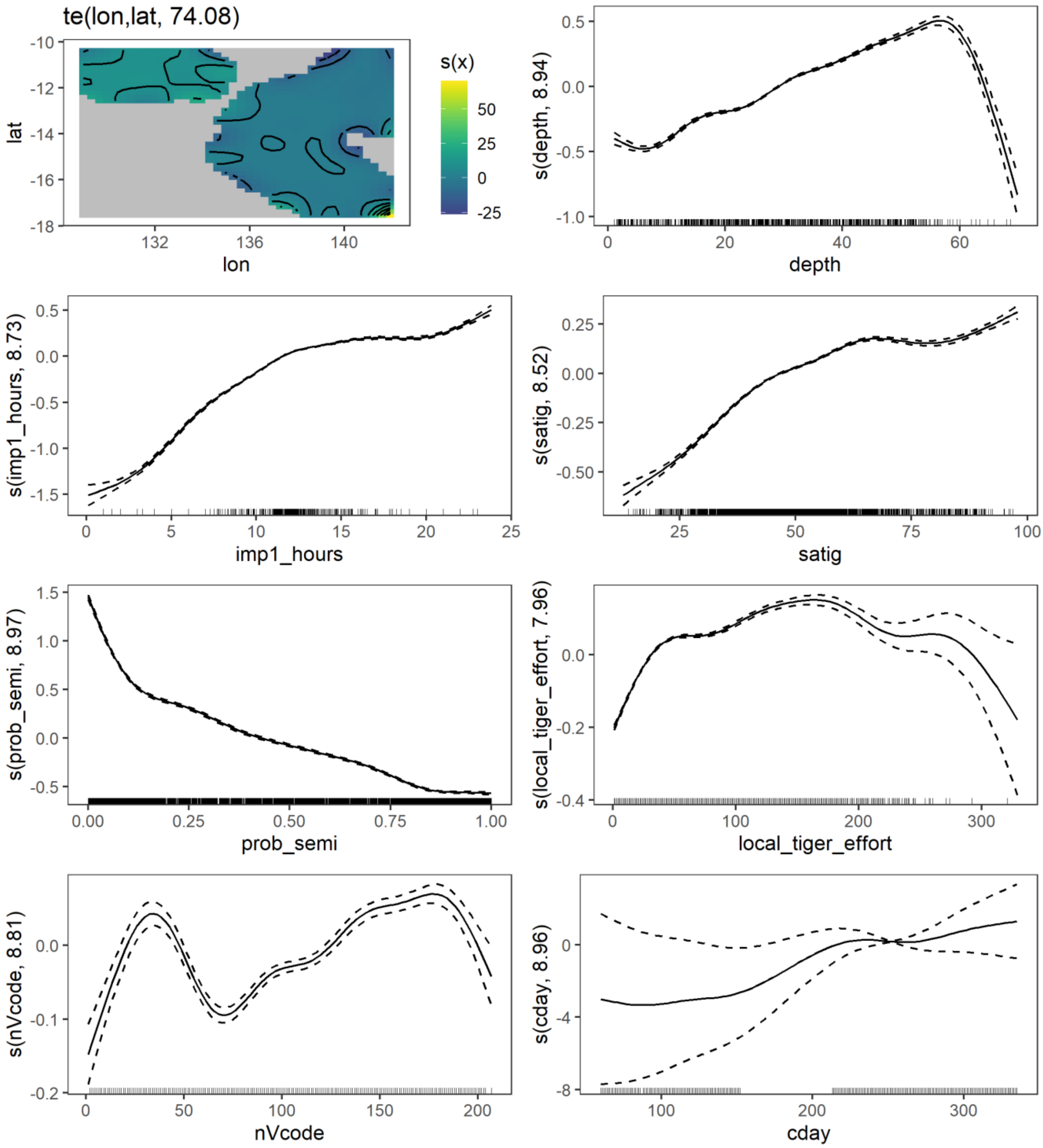


Figure 11. Effect of continuous variables on catch rate for the two endeavour prawn species as a group in Model 8, GAM-Tw2.

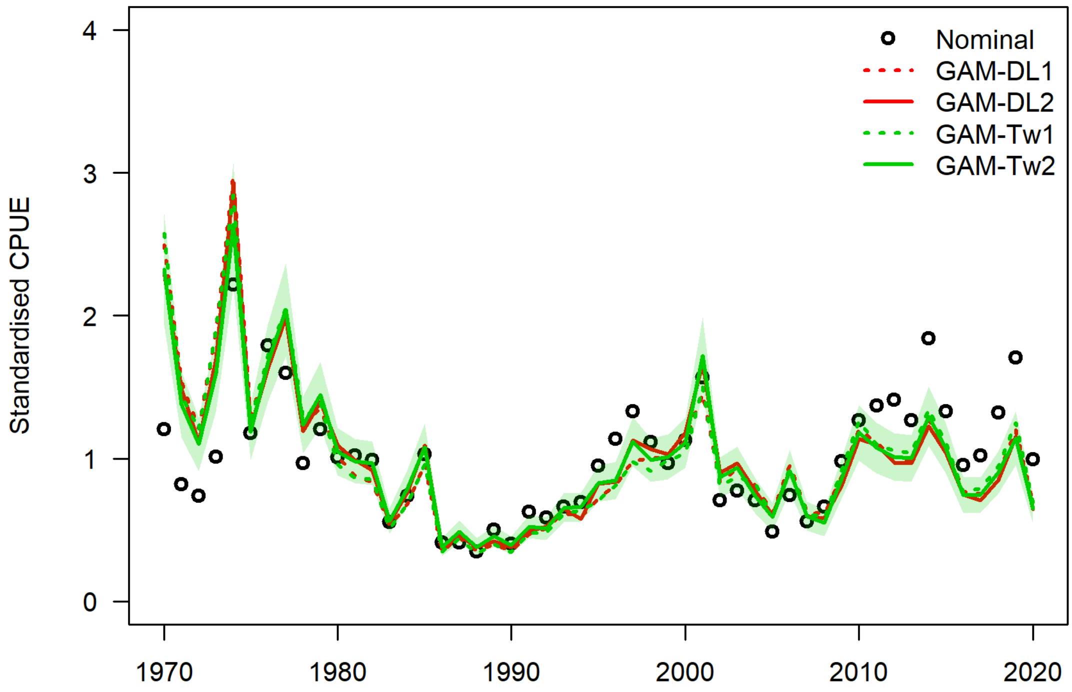


Figure 12. Abundance indices estimated by four alternative models for the two species of endeavour prawns as a group from 1970 to 2020. The green band is 95% confidence interval for Model 8, GAM-Tw2.

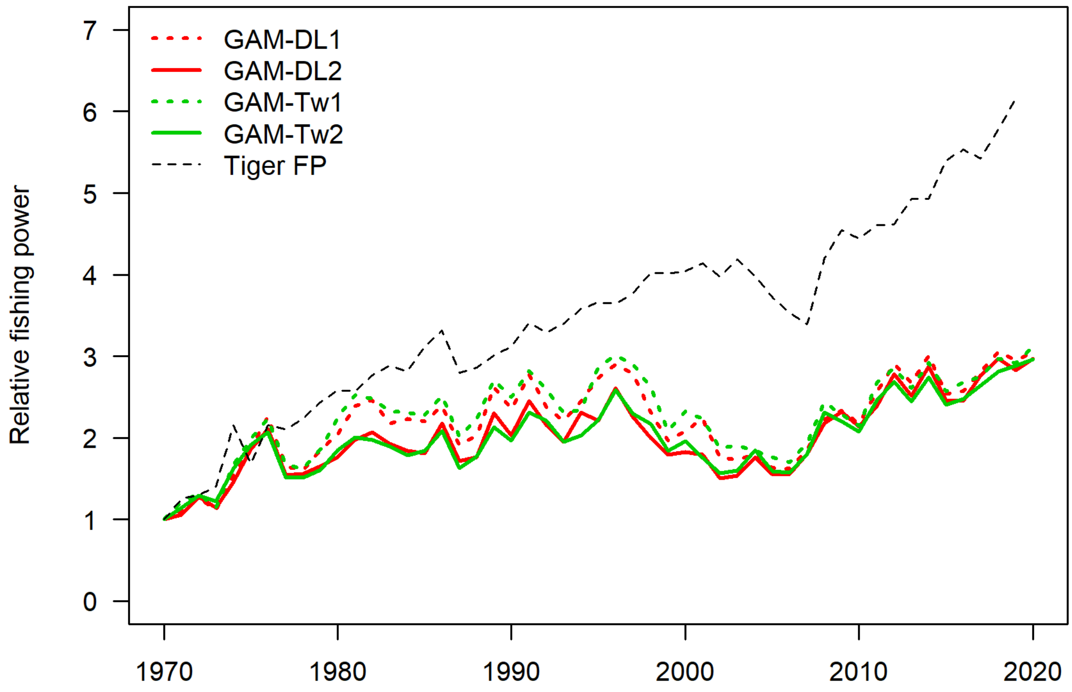


Figure 13. Relative fishing efficiency of the tiger prawn fleet on catching two species of endeavour prawns as a group from 1970 to 2020. The trends are estimated by four alternative generalized additive models. The latest available fishing power for tiger prawns is included as a comparison.

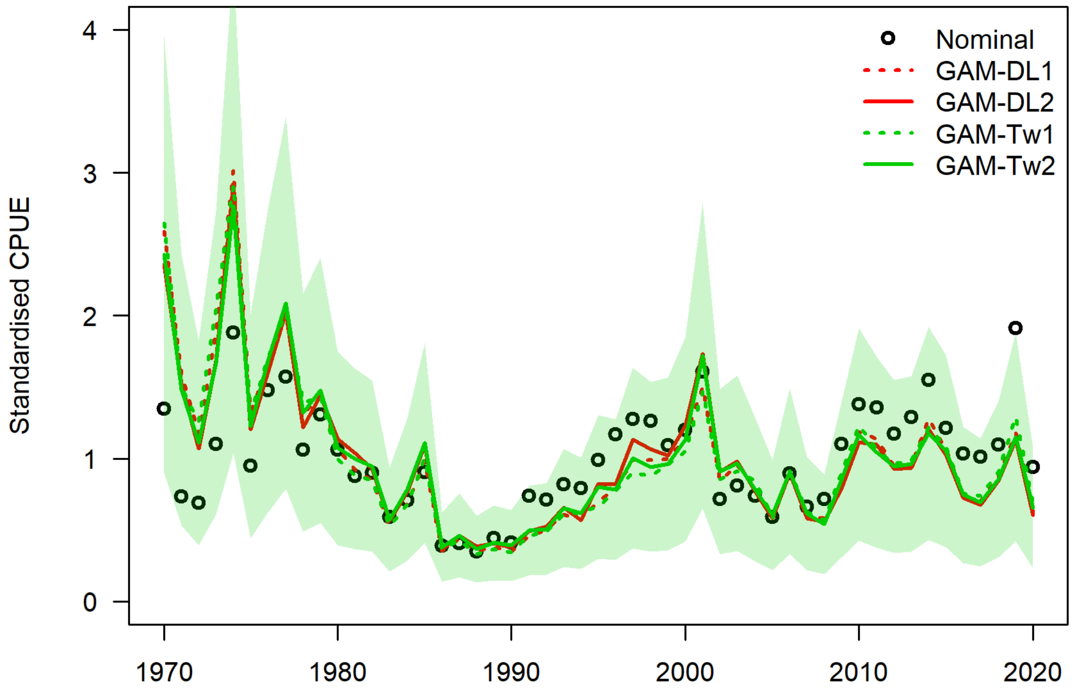


Figure 14. Abundance indices estimated by four alternative models for *blue endeavour* prawns from 1970 to 2020. The green band is 95% confidence interval for Model 8, GAM-Tw2.

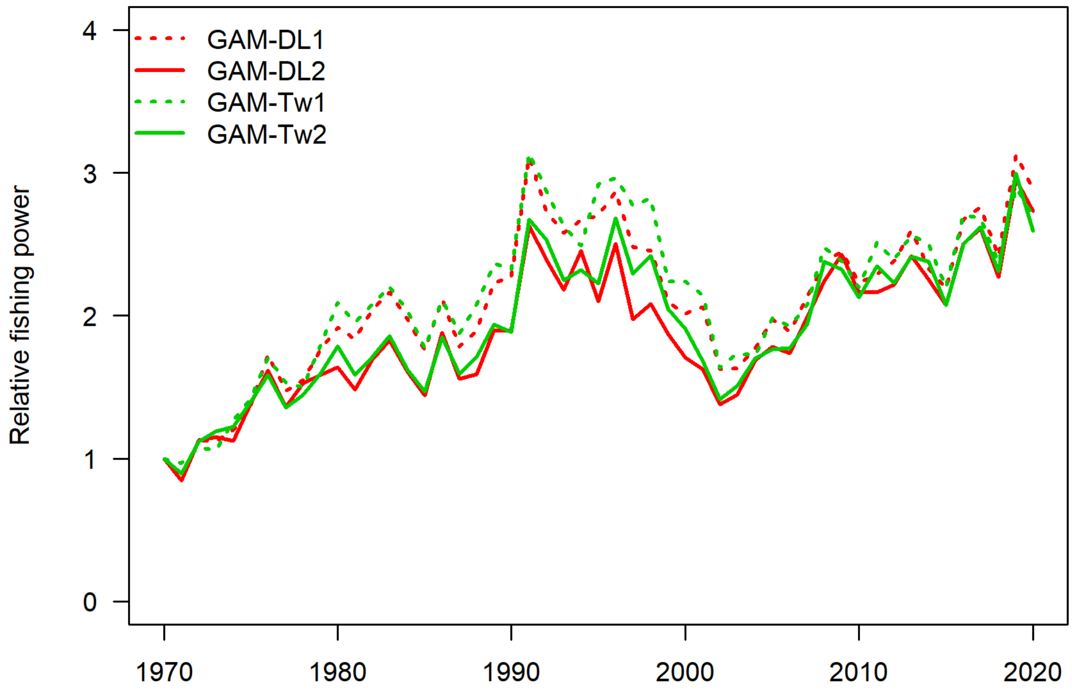


Figure 15. Relative fishing efficiency of the tiger prawn fleet on catching *blue endeavour* prawns from 1970 to 2020. The trends are estimated by four alternative generalized additive models.

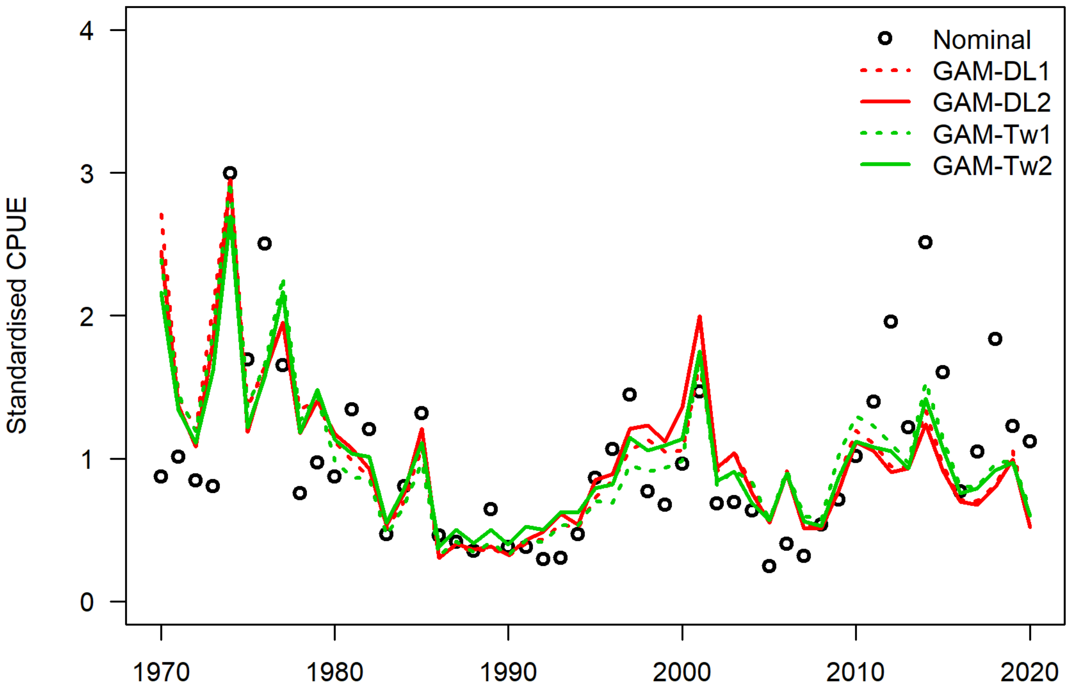


Figure 16. Abundance indices estimated by four alternative models for *red endeavour* prawns from 1970 to 2020.

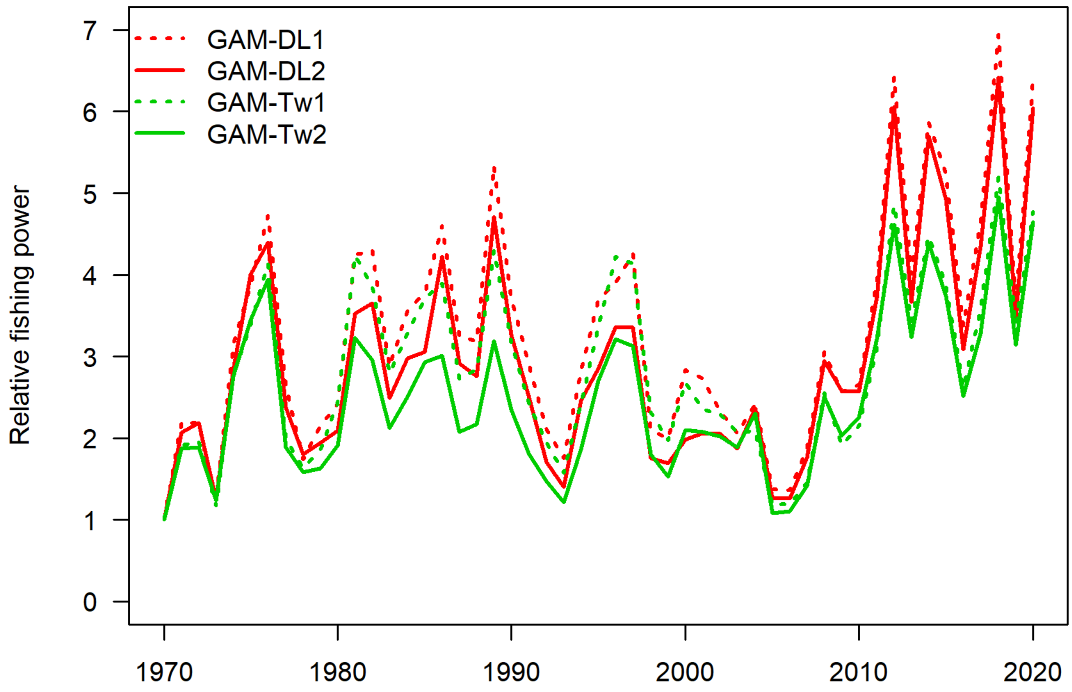


Figure 17. Relative fishing efficiency of the tiger prawn fleet on catching *red endeavour* prawns from 1970 to 2020. The trends are estimated by four alternative generalized additive models.

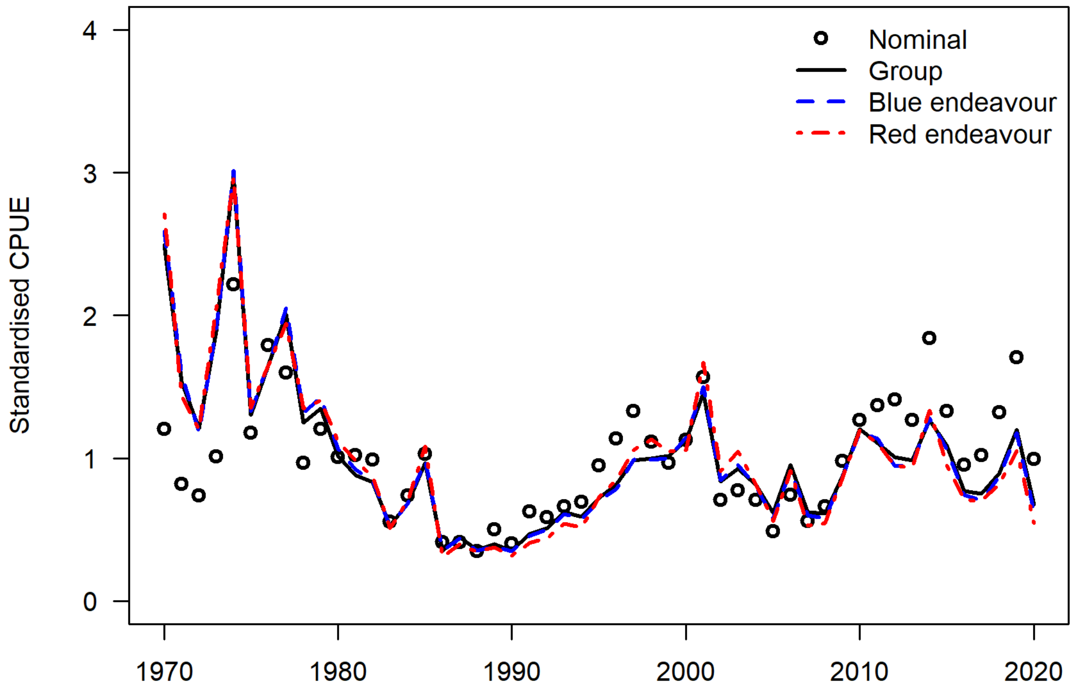


Figure 18. Comparison of abundance index estimated by Model 8, GAM-Tw2, for blue and red endeavour prawns as well as combined two species as a group.

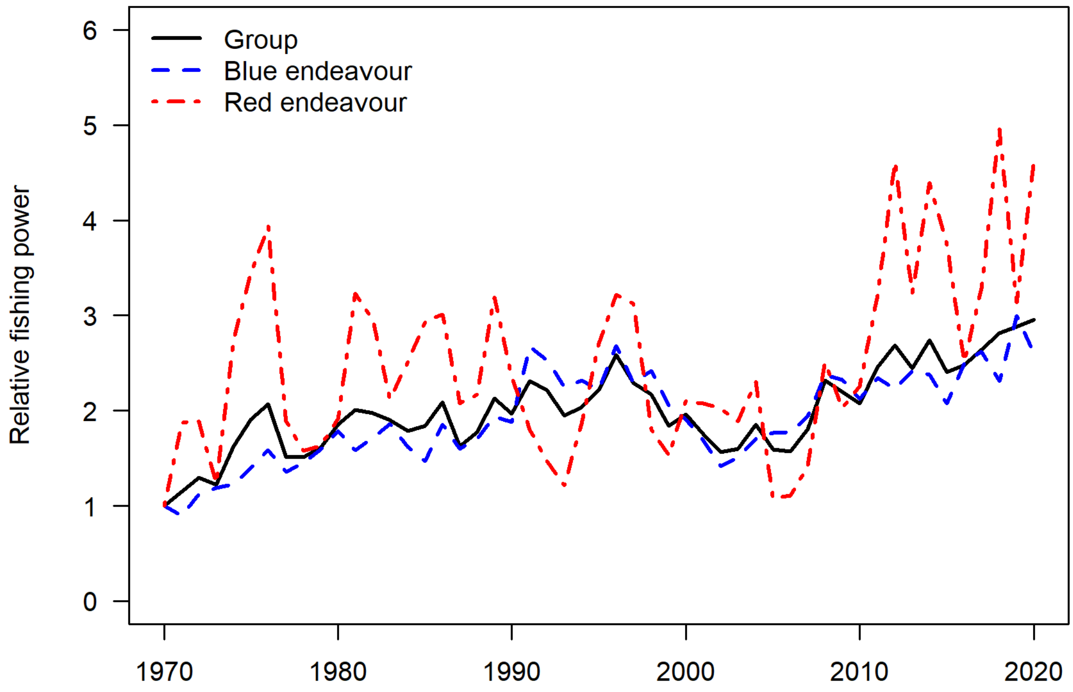


Figure 19. Comparison of relative fishing power estimated by Model 8, GAM-Tw2, for blue and red endeavour prawns as well as combined two species as a group.

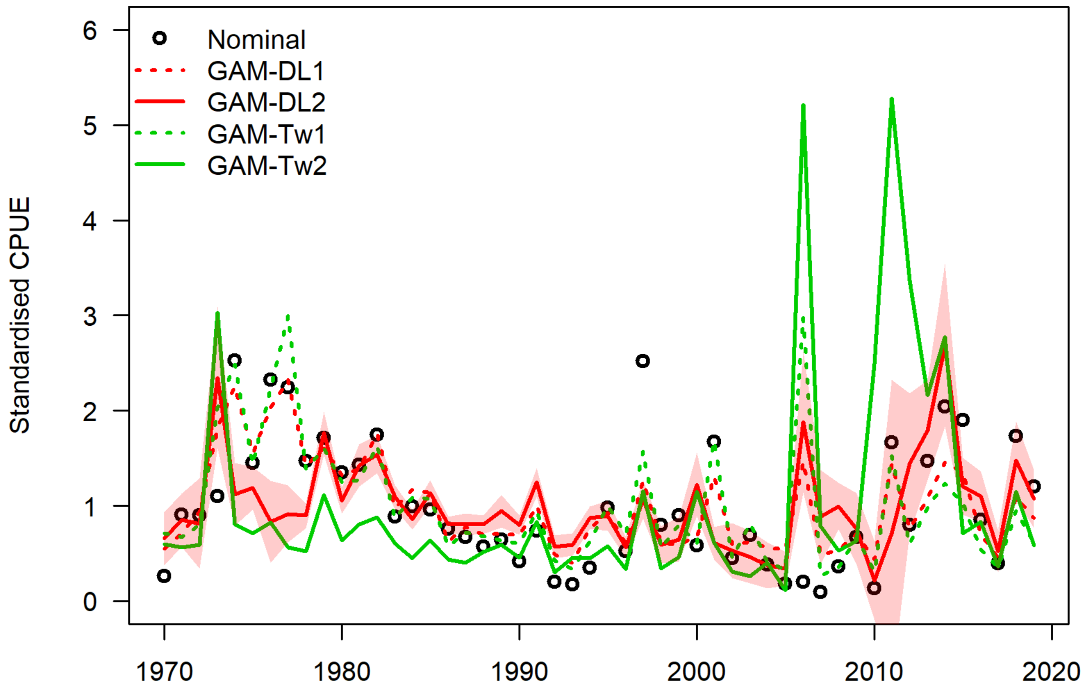


Figure 20. Abundance indices estimated by four alternative models for two species of *endeavour* prawns combined as a group in *Stock Region 1* from 1970 to 2020. The red band is the 95% CI for Model 6, GAM-DL2, which has the lowest MSE.

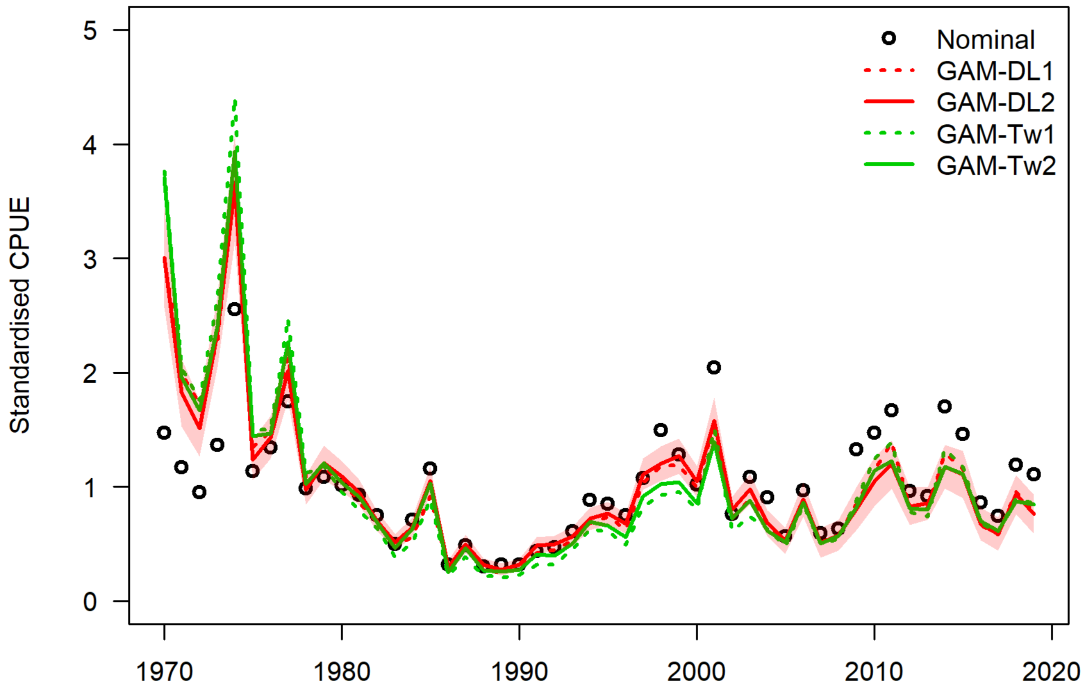


Figure 21. Abundance indices estimated by four alternative models for two species of *endeavour* prawns combined as a group in Stock Region 2 from 1970 to 2020. The red band is the 95% CI for Model 6, GAM-DL2, which has the lowest MSE.

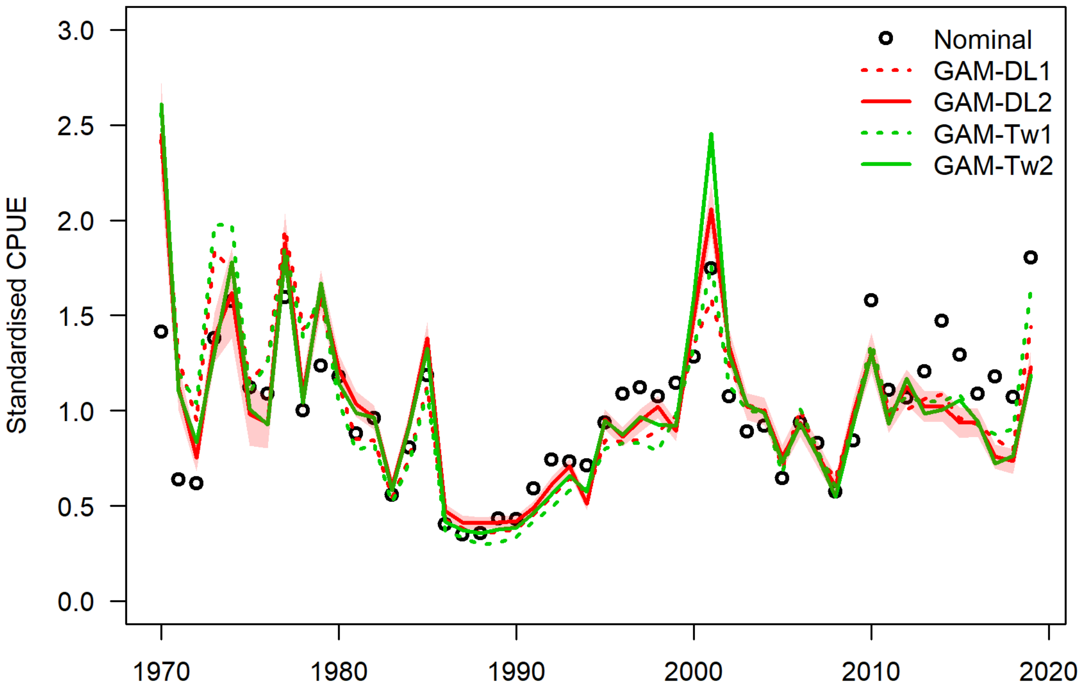


Figure 22. Abundance indices estimated by four alternative models for two species of *endeavour* prawns combined as a group in Stock Region 3 from 1970 to 2020. The red band is the 95% CI for Model 6, GAM-DL2, which has the lowest MSE.

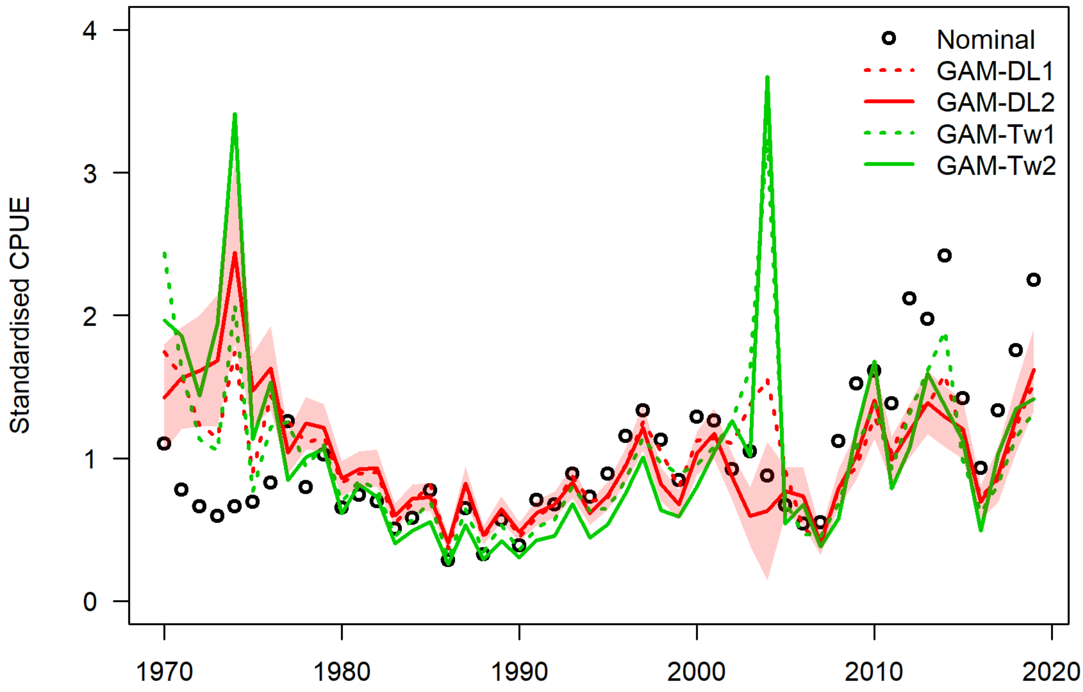


Figure 23. Abundance indices estimated by four alternative models for two species of *endeavour* prawns combined as a group in Stock Region 4 from 1970 to 2020. The red band is the 95% CI for Model 6, GAM-DL2, which has the lowest MSE.

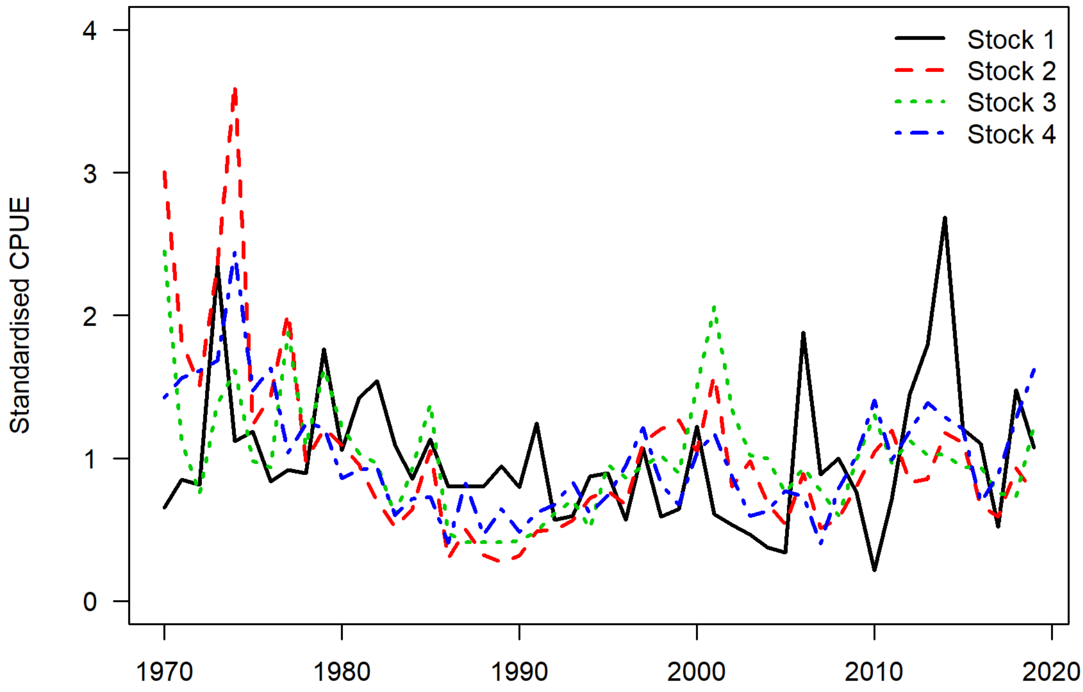


Figure 24. Comparison of abundance index estimated by Model 6, GAM-DL2 for two species of endeavour prawns combined as a group in four Endeavour Prawn Stock Regions.

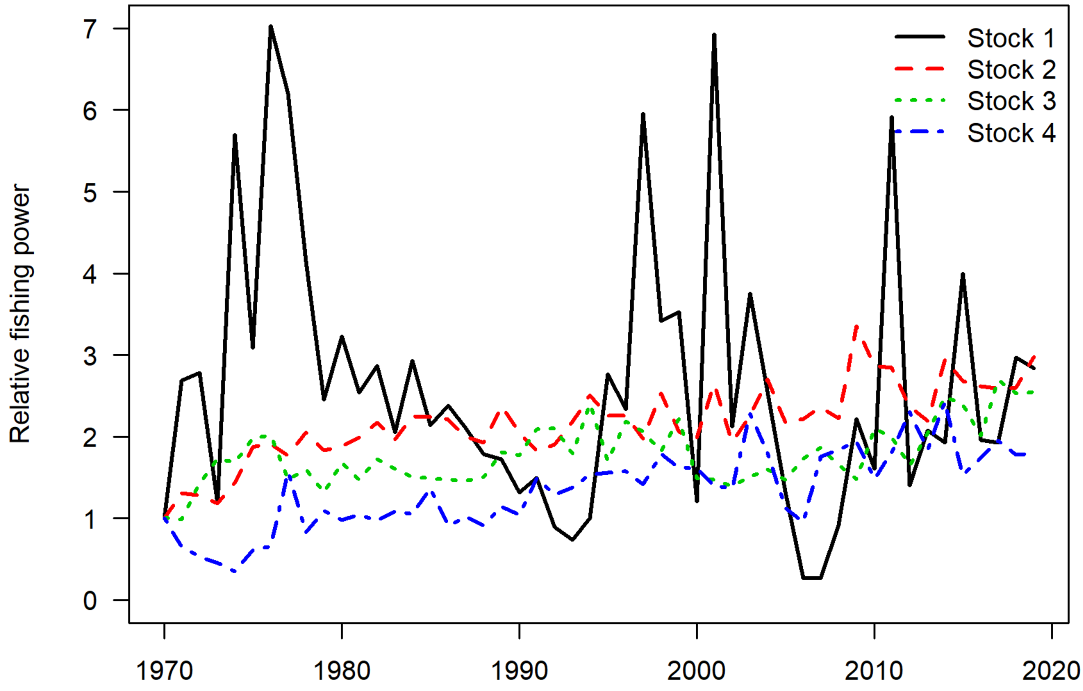


Figure 25. Comparison of relative fishing power estimated by Model 6, GAM-DL2 for two species of endeavour prawns combined as a group in four Endeavour Prawn Stock Regions.

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