Stock assessment of Queensland east coast tiger prawns (*Penaeus esculentus* and *Penaeus semisulcatus*), Australia, with data to December 2021

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Queensland Government

This publication has been compiled by R.A. Lovett, A.R. Fox, M.E. Wickens and K.B. Hillcoat of Fisheries Queensland, Department of Agriculture and Fisheries.

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Contents

Summary

This stock assessment indicates that the biomass of tiger prawns declined between 1958 and 1996 to a minimum value of 31% unfished biomass. The stock level for 2021 was estimated to be between 70% and 89%, and most likely at 79%, of unfished biomass.

'Tiger prawn' is a collective term for two species: brown tiger prawn (*Penaeus esculentus*) and grooved tiger prawn (*P. semisulcatus*). Brown tiger prawns are endemic to tropical and subtropical waters of Australia, while grooved tiger prawns have a wider Indo–West Pacific distribution. This assessment focuses on tiger prawns found on the eastern coast of Queensland. The species live at least two years and have a maximum observed size of 44 mm carapace length for brown females, 35 mm carapace length for brown males, 52 mm carapace length for grooved females and 38 mm carapace length for grooved males. Sexual maturity is reached at approximately 6 months of age and around 32–39 mm carapace length (Somers 1987).

A previous assessment estimated the Northern management region was 49% of unfished in 2019, and separately estimated the Central management region was at 50% of unfished in 2019. This assessment assumes a single tiger prawn population north of 22 degrees latitude and contains significant updates to data and methodology.

This stock assessment includes input data through to December 2021. All assessment inputs and outputs were referenced on a calendar year basis (that is, '2021' means January 2021–December 2021).

The assessment used a one-sex monthly delay-difference population model, fitted to catch rates. An age-structured model was also trialled, however this did not lead to outcomes that were considered plausible by the project team.

The model incorporated data spanning the period 1958 to 2021 including mandatory daily commercial logbook data collected by Fisheries Queensland (1988–2021), historic voluntary logbook data (1970–1988), Queensland Fish Board data (1958–1981), historic catch records (1958–2014), survey and logbook gear data collected by Fisheries Queensland (1988–2021), high resolution vessel tracking data collected by Fisheries Queensland (2000–2021) and lunar data (1958–2021). Length data collected by Fisheries Queensland (1998–2009) were also incorporated in a modelling scenario.

Over the last 5 years, 2017 to 2021, total retained catch averaged 1098 tonnes (t) per year (Figure 1). There was a decreasing catch trend through the late 1990s to the early 2000s. Fishery adjustment, including substantial reductions in boat numbers and fishing effort, was reflected in relatively reduced but stable catches from around 2006.

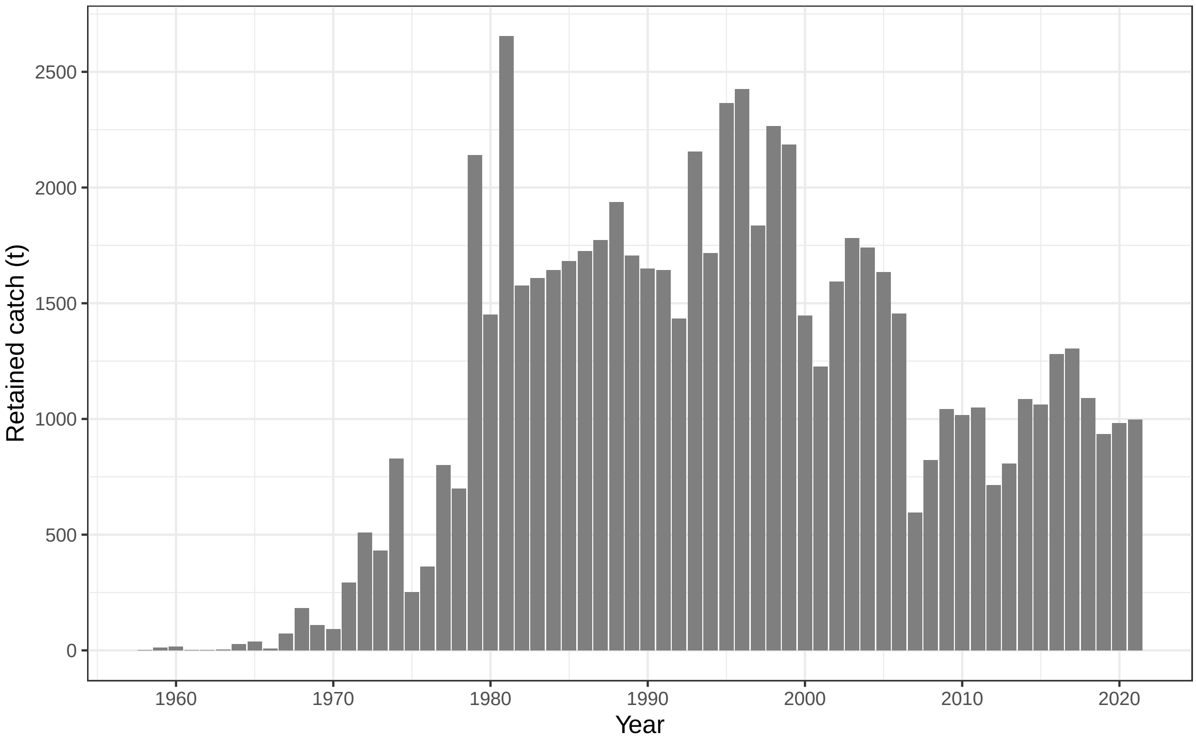

Figure 1: Annual estimated retained catch between 1958 and 2021 for Queensland east coast tiger prawns

Commercial catch rates were standardised to estimate an index of tiger prawn abundance through time (Figure 2). The unit of standardisation was kilograms of tiger prawn per 'operation-day', defined to be a single day of fishing by a trawl vessel. The catch rate standardisation model accounted for year, month, fishing grid, boat, number of hours trawls, lunar illuminance with waxing/waning reference point, fraction of grid available to trawling, fishing power offset and whether the species was targeted.

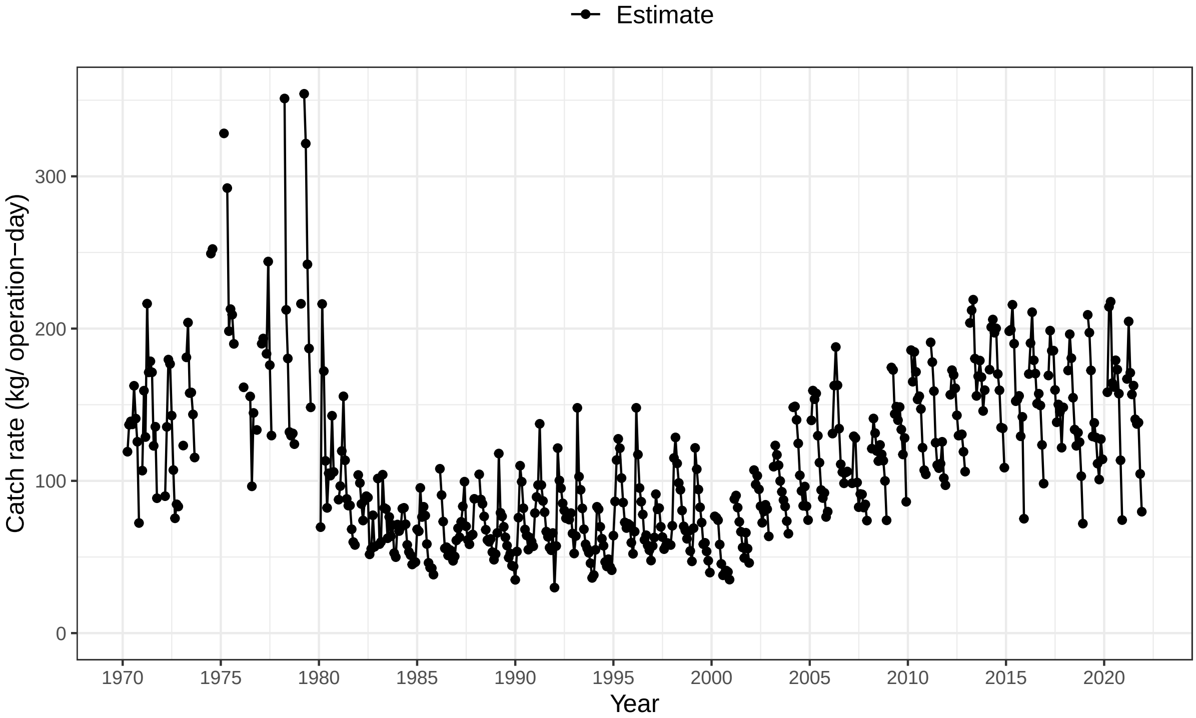

Figure 2: Monthly standardised catch rates relative to average kg per day for Queensland commercial tiger prawns between 1970 and 2021

The stock assessment was guided by a project team consisting of scientists, managers, and industry representatives. Ten scenarios were run using a delay-difference model, covering a range of modelling assumptions and sensitivity tests. All scenarios were optimised using Markov chain Monte Carlo (MCMC) to better explore the robustness of the models.

Project team preferred scenario results indicated that the tiger prawn stock experienced a decline from the period 1958 to 1996 to reach 31% of unfished biomass. The biomass has been steadily rising since this time, and in 2021 the stock level was estimated to be 79% of unfished biomass (70–89% range across the 95% credible interval) (Figure 3).

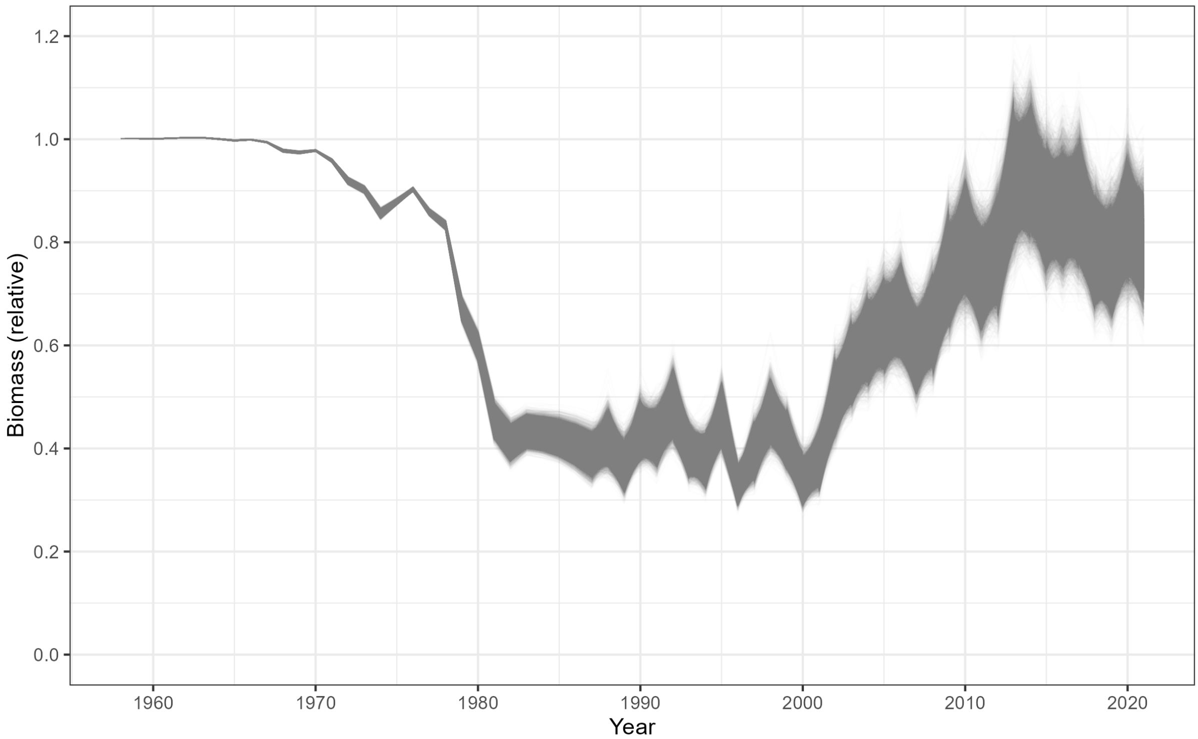

Figure 3: Predicted biomass trajectory relative to unfished for tiger prawns, from 1958 to 2021—grey lines represent individual MCMC samples

While the biomass ratio provides an indication of where the stock is currently, the fishing pressure gives an indication of where the stock is heading. The combination of biomass level and biomass direction provide a more complete picture of stock status (Table 1).

Table 1: Stock status indicators for east coast tiger prawns in 2021

Indicator	Estimate
Biomass (relative to unfished)	79% (70–89% credible interval)
Biomass direction	Decreasing
Catch	997 t

Given that the delay difference models were only able to be tuned against a single fishery-dependent data source (fisher catch rates), and that attempts to model the stock using additional data sets (e.g. length frequencies) using an age-structured framework were inconclusive, caution is recommended when interpreting the results presented in this report.

Acknowledgements

This stock assessment was guided by a project team with a wide range of skill sets. In addition to managers, scientists, monitoring and data specialists from within the Fisheries Queensland, the team included two industry representatives, and a scientific member external to Fisheries Queensland was added for the final three meetings. The project team operated under a terms of referencee[1] designed to ensure a transparent and evidence-based approach. The project team members were: Industry – Rik Buckworth and Gary Wicks; Fishery Management – Darren Roy, Lachlan Glaves and Luke Albury; Fishery Monitoring – Jason McGilvray and Andrew Prosser; Data Team – Tu Nguyen, Jennifer Larkin and Carlie Heaven; Ecological Risk and Policy – Anthony Roelofs and Brad Zeller; Stock Assessment – Fay Helidoniotis; Animal Science Queensland – Matthew Campbell; Chair – Alex Campbell. The entire team is thanked for contributing their time and knowledge, and engaging constructively over the course of a seventeen months-long project.

The authors acknowledge the significant time commitment, and deep operational and technical expertise, of our industry representatives Rik Buckworth and Gary Wicks. The project has benefited greatly from their input. Future assessments should aim to continue to engage with industry members to further enhance assessments and build collaboration between industry and government.

Michael O'Neill provided invaluable advice during the implementation of the delay-difference population models used in this assessment, and we thank all the authors of O'Neill et al. (2006a), Helidoniotis (2020), Courtney et al. (2014b), O'Neill et al. (2014), and O'Neill et al. (2005) for providing foundations which were built upon.

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[1] Publicly available on the Department's stock assessment webpage.

Glossary

BRDs	bycatch reduction devices
compulsory logbooks	the compulsory commercial logbook database managed by Fisheries Queensland
CI	credible interval
CL	carapace length
CV	coefficient of variation
fleet	a Stock Synthesis modelling term used to distinguish types of fishing activity: typically a fleet will have a unique curve that characterises the likelihood that fish of various sizes (or ages) will be caught by the fishing gear, or observed by the survey
DDUST	Delay-Difference with User Specified Timestep
ECOTF	East Coast Otter Trawl Fishery
GLM	generalized linear model
GPS	Global Positioning System
harvest	see 'retained catch'
HTRAWL	historic voluntary logbook records
MCMC	Markov chain Monte Carlo
MLE	Maximum likelihood estimate/estimation
MSY	maximum sustainable yield—the maximum level at which the species can be routinely exploited without long-term depletion
operation-day	a single day of fishing by a primary vessel, with year, month, stratum, number of dories and number of crew and combinations of these as explanatory terms
RAP	Representative Areas Program
REDDUST	Random Effect Delay-Difference with User Specified Timestep
REML	restricted maximum likelihood
retained catch	component of the catch that is kept by fishers, also referred to as 'harvest' and 'landed catch'
SR	stock recruitment
SS	Stock Synthesis
TEDs	turtle exclusion devices
TMB	Template Model Builder

1 Introduction

Grooved tiger prawns (*Penaeus semisulcatus*) and brown tiger prawns (*Penaeus esculentus*) are two species that form part of the collective group known as tiger prawns whose name originates from the striped pattern covering their shell.

Grooved tiger prawns are widely distributed throughout the Indo-West Pacific region (Somers et al. 1991) while brown tiger prawns are endemic to the tropical and subtropical waters of Australia (Somers et al. 1984; Somers 1987; Turnbull et al. 2007; Ward et al. 2006). Both species occur along the coastline of northern Australia from Shark Bay in Western Australia to the eastern coast of northern New South Wales (Somers 1987; Ward et al. 2006).

There are some differences in the migratory behaviour of both species with the grooved tiger prawn displaying more mobile behaviour with regular movements from the inshore feeding grounds to spawn in offshore waters, whereas the brown tiger prawn is more sedentary in nature (Dichmont et al. 2001; Venables et al. 2004). This implies that each species' susceptibility to capture differs throughout the coastline regions as most prawns typically migrate somewhat short distances (30–60 km) (Turnbull et al. 2007).

Spawning activity peaks periodically from January to March and August to October each year with female tiger prawns spawning in offshore waters with depths of less than 50 m (Turnbull et al. 2007). Approximately two weeks after spawning, post larvae settle on inshore sea-grass nursery beds within the estuary (Turnbull et al. 2007). After three months in the nursery grounds, young juveniles begin to migrate back to offshore waters, reaching maturity at approximately six months of age and around 32–39 mm carapace length (Somers 1987; Turnbull et al. 2007). Both grooved and brown tiger prawns have an approximate life cycle of 2 years (Dichmont et al. 2006; Somers et al. 1991).

Fishing for tiger prawns in Queensland occurs within the East Coast Otter Trawl Fishery, predominantly in the northern and central trawl regions. The fishery operates within the Great Barrier Reef Marine Park and is located along the corridor formed by the Great Barrier Reef between the coast and offshore to 200 nautical miles, between the Torres Strait and Mackay (Turnbull et al. 2004; Turnbull et al. 2005; Turnbull et al. 2007). This report focuses on the tiger prawn stocks within the northern and central trawl management regions north of 22° S. Tiger prawns are a valuable, commercially-fished stock, with harvests of approximately 1098 tonnes annually in the last five years, and with a total annual landed value of about AUD 19 million dollars in 2020–2021 (Tuynman et al. 2022). There was a decreasing catch trend through the 1990s to the early 2000s. Fishery adjustment, including substantial reductions in boat numbers and fishing effort, was reflected in relatively reduced but stable catches from around 2006.

Management in Queensland applies a range of input controls including vessel entry limitations, boat-day/effort-unit allocations, vessel and gear size restrictions and spatial and temporal closures (Table 1.1). There are regional effort caps across five trawl management regions in the Queensland East Coast Otter Trawl Fishery including a specific effort cap within the Great Barrier Reef Marine Park. In northern Queensland, annual prawn surveys have been utilised in prior years to monitor prawn size, relative distribution and abundance with the intention of contributing to stock assessments, and documenting relative bycatch of the fisheries (Turnbull et al. 2005).

Table 1.1: History of prawn management in Queensland

Year	Fisheries Operations, Management and Regulations
1980	1400 licensed vessels
1983	Great Barrier Reef Marine Park closures
1984	Voluntary catch logbook scheme initiated (*Central Queensland Prawn Fishery*) (Dredge 1990)
1986	Great Barrier Reef Marine Park closures
1988	Compulsory commercial logbook reporting of catch commenced
1991–1992	Seasonal closures between 15 December and 1 March implemented north of Cape Tribulation (*Queensland east coast trawl fishery*) (Turnbull et al. 2004; Turnbull et al. 2005)
1999	Introduction of East Coast Trawl Management Plan Licence operators reduced from 1400 to 800 vessels
1999–2001	From November 1999 to June 2001 turtle exclusion devices (TEDs) and bycatch reduction devices (BRDs) gradually implemented in the Queensland East Coast Trawl Fishery (Courtney et al. 2007)
2000	Introduction of southern trawl plan and closure from 20 September to 1 November
2001	Revised plan: buy back and effort management system, effort unit trading system Introduction of an effort management system based on effort nights Area of seasonal closures between 15 December and 1 March extended down to Mackay from Cape Tribulation (Turnbull et al. 2004)
2002	*The Queensland Fisheries (East Coast Trawl) Fishery Management Plan 1999* mandated the use of turtle exclusion devices (TEDs) in all otter trawl vessels and bycatch reduction devices (BRDs) in every trawl net to reduce bycatch in Queensland (Courtney et al. 2007)
2002–2003	Increase in average boat size due to smaller boats (i.e. 10–40 hull units) leaving the fishery as a result of licences being bought out by the government buyback scheme
2004	Reduction of licence operators to 527 vessels Compulsory commercial logbook reporting of gear commenced Vessels use of computer mapping and global positioning systems Use of bycatch reduction devices and turtle exclusion devices
1 July 2004	*Representative Areas Program (RAP)* introduced a comprehensive rezoning of the whole Great Barrier Reef Additional areas of the Great Barrier Reef closed to trawl fishing
2012–2014	*East Coast Net Buy-Back Program* carried out and consisted of three separate buy-back schemes targeting commercial vessel licences
1 Sept 2019	Boat possession limits reduced to twice that of individual possession limits Strip closures implemented in the Southern Offshore Trawl Region between 2 November 2019 and 1 March 2020
30 Sept 2020	Maximum vessel size increased to 20 m maximum length (120 hull units)
1 Sept 2021	Queensland east coast trawl fishery begins new management under five regional harvest strategies across five separate trawl zones Standardisation of reporting requirements commences with an upgrade to the Automated Integrated Voice Response system

In 2022, the Queensland Department of Agriculture and Fisheries commenced a stock assessment for five prawn species: two tiger prawns species (*Penaeus semisulcatus* and *Penaeus esculentus*), red spot king prawns (*Melicertus longistylus*) and two endeavour prawn species (*Metapenaeus endeavouri* and *Metapenaeus ensis*). Tiger prawns have previously been assessed at the sector level (northern and southern sectors, split at 16° S) by Wang (2015) and at the management region level by Helidoniotis (2021), using a weekly delay-difference model. Helidoniotis (2021) estimated the stock was at around

49–50% of unfished levels in 2019 for the central and northern trawl management regions. This assessment treats the population as a single, reproductively connected stock, and includes several other significant updates to the methodology and input data. A comprehehsive "bridging analysis" showing all the changes and their impacts is included in Appendix E. The objective of this stock assessment is to determine current stock biomass relative to an unfished state to inform management of the East Coast Otter Trawl Fishery.

This stock assessment was completed in tandem with those of red spot king prawns (Fox et al. in press[a]) and endeavour prawns (Fox et al. in press[b]) on the Queensland east coast. Many of the same methods were used to develop the models and model inputs for all three assessments.

2 Methods

2.1 Data sources

Data sources included in this assessment (Table 2.1) were used to determine catch rates, length compositions, and create annual harvests. The assessment period began in 1958 up until and including 2021 based on available information.

Table 2.1: Data used in the Queensland east coast tiger prawn stock assessment

Data	Years	Source
Commercial harvest and effort	1989–2021	Logbook harvest data collected by Fisheries Queensland
	1941–1981	Queensland Fish Board data (Halliday et al. 2007)
	1952–2014	Historic catch records (Hutchison 2015)
	1988–2004	Survey gear data collected by Fisheries Queensland
	2006–2021	Logbook gear data collected by Fisheries Queensland
	2000–2021	High resolution vessel tracking data collected by Fisheries Queensland
	1968–1990	HTRAWL data (O'Neill et al. 2005)
Biological	1998–2009	Biological monitoring (species, sex and length from the commercial fishery) undertaken by Fisheries Queensland (Fisheries Queensland 2012b)
Lunar	1958–2021	Continuous daily luminous scale of 0 (new moon) to 1 (full moon) from R package 'lunar' (Lazaridis 2014)

2.1.1 Regions

This assessment considered the spatial scope to be all east coast Queensland latitudes south of 11° S and north of 21° S, plus between 21° S and 22° S west of 152.5° E (Figure 2.1). This latter stipulation is in place to include shallow water areas where tiger prawns are found and exclude deep water areas where they are not. This spatial stock boundary, except for the northern boundary, is the same as that which was used in O'Neill et al. (2006b). High resolution vessel tracking data were analysed to determine the location of tiger prawn catch, identifying minimal catches below 22° S and above 23° S. This suggests a lack of connectivity between prawns caught in the defined assessment regions and those caught below 23° S, supporting the work of O'Neill et al. (2006b). This disconnect is possibly due to extreme tidal currents creating forces on the seabed in both inshore and offshore areas that lead to sediment scoured and epibenthic habitats that rarely occur in northern regions where tiger prawns are more commonly found (Pitcher et al. 2007). In the macrotidal areas of Broad Sound and Shoalwater Bay (both located at a latitude of 22° S), tidal currents are the dominant force influencing the mobility and grain size properties and contrasted with the rest of the Great Barrier Reef Marine Park (Porter-Smith et al. 2004).

Regarding the northern boundary, literature suggests tiger and endeavour prawns move predominantly east-west through the Torres Strait (from the west of Warrior reefs into the east of fishing ground), with minimal north-south movement (Watson et al. 1993). Tagged tiger prawns in the Torres Strait moved an average of 4–27 nm (maximum 69 nm, roughly the distance from Cape York to Papua New Guinea; Ward et al. 2006). For this reason the Torres Strait was excluded from the assessment area.

Historically there have been three partial fishery closures which have cumulatively limited the spatial extent of the fishery area available to trawling (Figure 2.1). These closures occurred in 1983, 1986 and 2004. The impact that the closures in 2004 had on catch are well understood, through studies like Hand (2003) and analysis of high resolution vessel tracking data from before and after the closures. The 1986 closure is less understood, however understanding was guided by historic harvest data and industry feedback. The 1983 closure had, according to industry feedback, minimal impact on the tiger prawn fishery so has been disregarded for the purposes of this assessment. Changes in fishery zoning over time, and subsequent limitations to trawling, could influence the estimate of biomass if not suitably captured in the modelling process. Although the change in catch can be quantified, the effect on apparent population dynamics like relative abundance within and outside of closures, or changes in fisher behaviour can not be accurately modelled without supporting data. This assessment considered the impact of fishery zoning changes through the use of a covariate in the catch rate standardsiation model (Section 2.3) and in how the catch rates were used in the population model through the use of different modelling scenarios (Section 2.5.5).

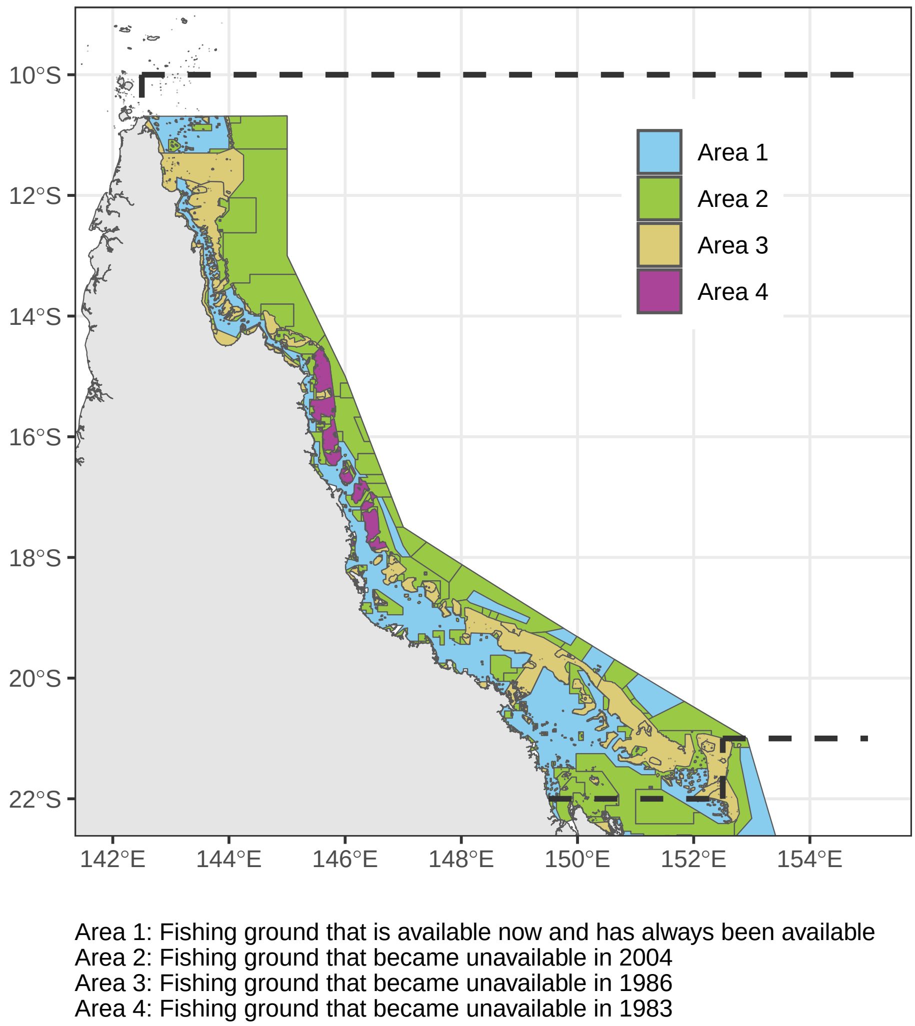

Figure 2.1: Assessment region defined by dashed lines—coloured fill represents changes through time of available trawling area within the defined assessment region

2.1.2 Commercial

Commercial harvest and effort data associated with tiger prawns have been recorded in the Queensland logbook system from 1988 to present. The logbook system consists of daily retained catches (landed whole weight in kilograms) of all fish species from each fishing operator (licence). In addition to landed weight for each boat/licence each day, logbooks record data such as the location of the catch (30 minute or 6 minute grid identifier), and information on gear and vessels such as otter boards, net type, gear type, bycatch reduction devices and turtle excluders (BRD and TED), computer mapping, fuel capacity, fuel use, ground chain (mm), global positioning systems (GPS), engine rated power (hp), vessel length, mesh size, net size, propeller nozzle, propeller pitch, propeller diameter, reduction, sonar, speed, and the use of try gear.

Historical retained catch (prior to 1988) was based on Queensland FishBoard data (1945–1980), information documented in Hutchison (2015) (1947–1981) and linear interpolation to fill the 1981–1988 gap in the available estimates. It is recognised that not all fish were sold via the Queensland FishBoard and that not all fish reported from a depot would have originated from the genetic stock identified for this assessment. Sensitivity tests guided by input from industry were included to test the affect of the possible underestimation or overestimation in these data.

Historic catch and effort information were also sourced from voluntary logbook catch data collected between 1968 and 1987 prior to implementation of the compulsory logbook system in 1988. These data are herein referred to as 'HTRAWL'. HTRAWL data were of varying quality and quantity and initially described in Section 8.3.7 of O'Neill et al. (2005).

2.1.3 Recreational, Indigenous and charter

Recreational, Indigenous and charter harvests were non-existent or negligible for tiger prawns and were not included in this assessment.

2.1.4 Length data

Fishery dependent length data from the Fisheries Queensland biological monitoring program (Fisheries Queensland 2012b) were collected over the period 1998–2009. These data were used for Stock Synthesis modelling inputs (Appendix G).

In addition, these data gave information on the species split proportions of grooved tiger prawns (*Penaeus semisulcatus*) to brown tiger prawns (*Penaeus esculentus*), enabling estimation of collective species biological parameters.

2.2 Retained catch estimates

2.2.1 Logbook retained catch

For tiger prawns, in addition to a logbook 'tiger prawns' category, there was also a category which contained a mix of tiger prawns with other prawn species: 'Prawn - king + tiger'. For this category it was necessary to allocate the correct proportion to tiger prawn. The steps used to determine the split of this category are as follows:

1. Determine species proportions to apply to each group.
    - Species proportions were determined in two scales:
        (a) kilograms for each month-grid-site
        (b) kilograms for each month-grid
    - For species reported as 'Prawn - king + tiger', determine proportions for each known species (tigers, red spot king, blue leg king, eastern king).
2. For each entry of each species group with known grid and site information, apply the species with the greatest proportion in each month-grid-site.
3. For each remaining entry of each species group with known grid information, but unknown site information, apply the species with the greatest proportion in each month-grid.
4. For data used to create catch rates, the remaining records with no grid information were omitted.
5. For data used to create catch estimates, the remaining records with no grid information were split on a proportion per year-month basis.

2.2.2 Historical retained catch

Historical harvest reconstruction was performed with the following steps:

1. From the first 5 years of logbook data, a monthly species proportion of all prawns was obtained.
2. FishBoard data were obtained for all prawns combined. It was considered that these data did not adequately reflect the amount harvested at the time (Appendix D). These data however, contained regional information and from this an annual regional proportion was obtained.
3. Harvest data for all of Queensland were obtained from Hutchison (2015) page 102–103, Table 4. These data were then shaped as follows:
   (a) The annual regional proportions found from the FishBoard data in step 2 were applied, reducing the data to harvest only for our region of interest.
   (b) The monthly species proportions found in step 1 were then applied.
   (c) It was considered that the harvest for red spot king prawns was still too high (Appendix D). The red spot king prawn harvest was reduced by half and these discarded kilograms of prawns were distributed to all other prawns using the proportions found in step 1 (Appendix D)
4. The remaining years between the data found in Hutchison (2015) and compulsory logbook (1982–1987) were determined by log-linear interpolation of the available harvest estimates following the method set out in Leigh et al. (2017). The harvest for each interpolation year is given by

$$C_{x+i} = C_x^{(d-i)/d} C_y^{i/d},$$

   where C_x and C_y represent the known harvests for years x and y that we wish to interpolate between, the denominator $d = y - x$ and $i \in [1, (d-1)]$.

2.3 Standardised indices of abundance

Queensland logbook records and historic voluntary logbook records (HTRAWL) of commercial retained catch of tiger prawn (kg whole weight) per boat per day were used as an index of legal-sized fish abundance. The index was standardised to remove the influence of a number of factors not related to abundance. This section outlines the standardisation procedure.

2.3.1 Data filtering

To proceed with catch rate analyses, the logbook data required filtering to produce one record per boat-day, with each boat-day including just one location (the 6' reporting grid in which most of the catch by volume was caught).

To produce reliable indices of abundance that avoid confounding influences on catch rates (e.g., fisher experience, vessel specific fishing power, or shifts in fishing behaviour like targeting), the fishers and grid cells that did not substantially contribute to the fishery, or that were not representative of the fishery, were removed prior to catch rate analysis per the following filters:

- The data were reduced to only fishing records that used the otter trawl fishing method
- Records for the same boat fishing on the same day were combined into a single record:
  - All catch for the day was assigned to the grid with the greatest catch
  - 'Hours fished' for the day was calculated as:
    - the maximum hours of each record for logbook data
    - the sum of hours of each record for HTRAWL data
- The data were reduced to the stock assessment region
- The data were reduced to boats who fished in more than one year
- The data were reduced to only boats that caught the top 99% of catch
- The data were reduced to only fishing grids where the top 95% of catch was recorded

Fishing grids resulting from this filtering process are displayed in Figure 2.2. After data filters were applied, the remaining catch rate data spanned from 1970 to 2021.

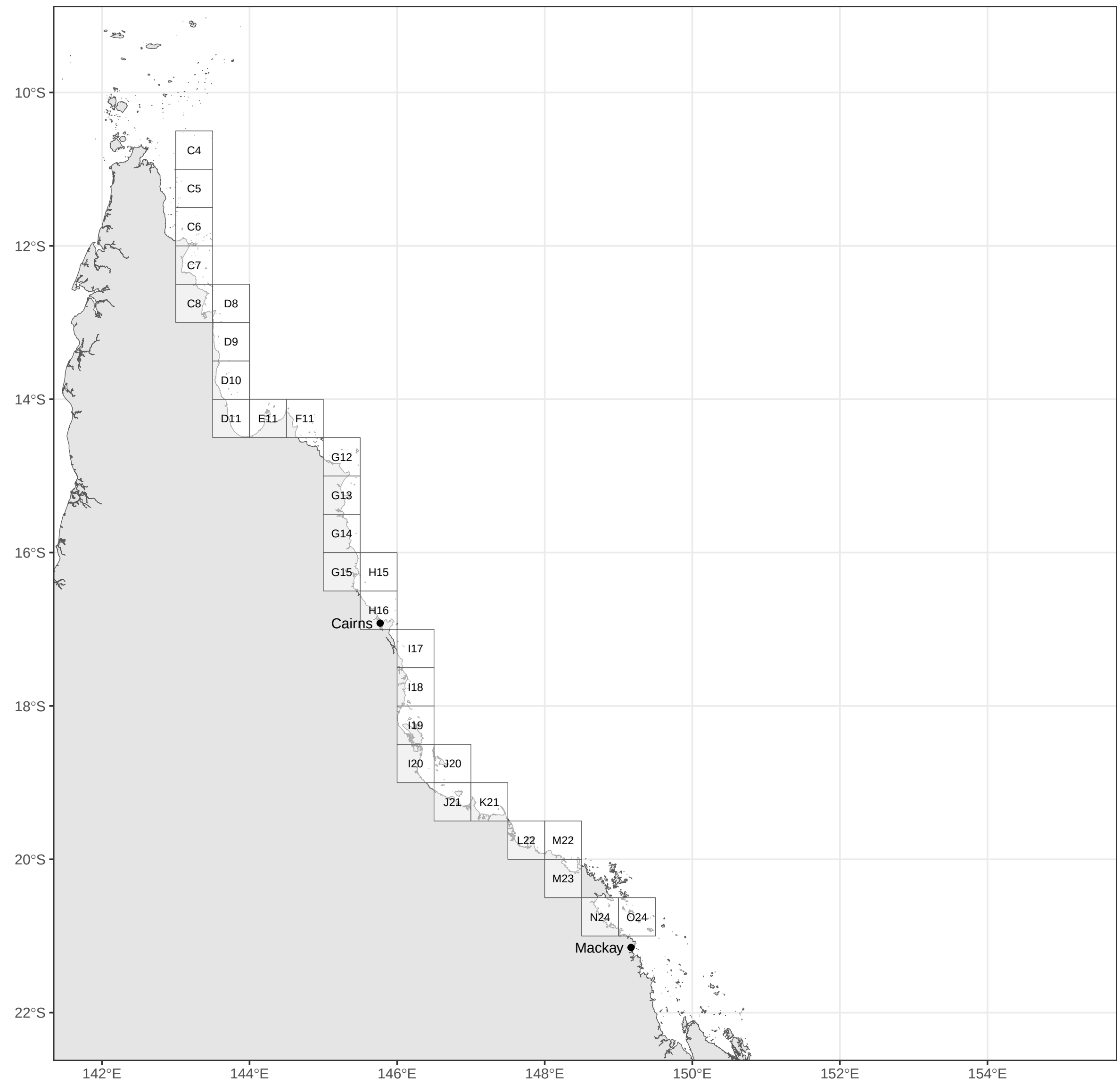

Figure 2.2: Logbook grids that were used in the catch rate analysis for tiger prawns after data filters were applied

2.3.2 Targeting

Tiger prawns are not always a primary target species in the ECOTF, likely resulting in many zero catch records. Zero catches may originate from fishers targeting other species and thereby trawling unsuitable areas for tiger prawns. Alternatively, fishers may have tried fishing in a suitable tiger prawn area but failed to catch any tiger prawns. The first scenario does not give insight into the abundance of tiger prawns, but the second scenario does. In the case that the fisher was operating in a suitable tiger prawn area but failed to catch any tiger prawns, the record is deemed a ‘true zero’ catch. In the case that the fisher was not operating in a suitable tiger prawn area and did not catch tiger prawns, the record is deemed a ‘false zero’.

Identifying whether a fisher intended to target tiger prawn for a given fishing record is a valuable tool to identify false zeroes and subsequently standardise catch rates. In the context of this assessment, this targeting analysis informs if the catch rate of a particular species in a particular fishing operation should be included in the standardised catch rate series to develop an index of abundance.

For each year, month, grid, a simple probability model was used to determine the likelihood of finding a tiger prawn, if other species were present. Following methods used in Dichmont et al. (2001), correlations were calculated between different species (i.e. likelihood of finding two species in the same trip). This analysis found positive association between tiger and endeavour prawns, and negative association between tiger and red spot king prawns. This helped to refine the probability model and data rule: the catch record was considered to be targeting tiger prawns if the probability of finding a tiger prawn (in the year x month x grid) was greater than the probability of finding a red spot king prawn.

2.3.3 Fishing power

Fishing power estimates were based on Queensland trawl logbook data consisting of daily catch and effort information per vessel (1988–2021) paired with gear usage and vessel information from surveys described in O’Neill et al. (2006a) and O’Neill et al. (2006b). Logbook data were subset to only include records that had matching gear usage and vessel information, and the fishing power was analysed using logbook records and boat gear data together.

Fishing power refers to how adoption of technology and gear advancements improve prawn catchability through time. Changes in fishing power are real world effects and must be considered. An annual change in fishing power relative to 1989 was calculated using the uptake of computer mapping, GPS, bycatch reduction devices, turtle excluder devices, as well as the type of otter board, type of ground gear, number of nets, trawl speed, and horsepower. Prior to 2004, gear information was collated by O’Neill et al. (2006a). In 2006, gear description sheets were introduced in the ECOTF. Fishing power in 2005 was taken as the average of 2004 and 2006 fishing power estimates. Fishing power for tiger prawns was included in the catch rate standardisation GLM as a log-transformed offset.

Prior to estimating fishing power, a collinearity check was conducted to determine which variables were related of all the variables considered (engine rated power (hp), fuel capacity, net size, the use of try gear and ground chain (mm)). Any variables that were related cannot all be fitted simultaneously, and therefore only one of those variables was selected to be used in the subsequent linear mixed model. Fishing power was estimated using a linear mixed model with REML in GenStat software (VSN International 2019):

$$\begin{aligned} \log(\textit{weight}) \sim & \textit{year} * \textit{month} * \textit{grid} + \textit{lunar} + \textit{lunaradv} + \log(\textit{hours}) + \log(\textit{hp}) + \\ & \log(\textit{speed}) + \textit{nettype} + \textit{ggear} + \textit{boards} + \textit{brdted} + \textit{gps} + \textit{compmap} \end{aligned} \tag{2.1}$$

where:

- $\log(\textit{weight})$ is the log transform of weight of prawns caught in kilograms,

- fishing year (*year*) and fishing month (*month*) relate to the fishing season for tiger prawns which is the same as the calendar year,
- *lunar* is the luminosity of the moon, lunar advance (*lunaradv*) differentiates whether the lunar phase was waxing or waning,
- $\log($*hours*$)$ is the log of the hours fished per boat per day,
- $\log($*hp*$)$ is the engine rating in horsepower,
- $\log($*speed*$)$ is trawling speed,
- *nettype*, *ggear* and *boards* are factors representing type of net, ground gear and boards used, and
- and *brdted*, *gps* and *compmap* are binary variable representing the presence of bycatch reduction devices and turtle excluder devices (BRD/TEDs), GPS and computer mapping.

The output of the fishing power linear mixed model is an annual fishing power offset for the entire assessment area from 1988 to 2021, which is used as part of the standardised catch rate model. The standardised catch rates include logbook data back to 1970 so the fishing power offset was hindcast for this earlier period. This was done by estimating the fishing power offset in 1970 and linearly interpolating between 1970 and 1989. Using the estimated coefficients from Equation 2.1, the expected fishing power offset in 1970 was calculated assuming the following: computer mapping, GPS, BRD/TEDs, boards were non-existant; the ground gear used was the same as the average of that used between 1988 and 1990; the value of double, triple and quad nets were equal to that in 1988; the trawl speed was 2.5 km/hr and the engine rating was 200 HP.

2.3.4 Standardisation model

Standardised catch rates were calculated using REML in Genstat using linear mixed models (REML) and assumed normally distributed errors on the log scale (VSN International 2019). The log transform of the weight of prawns caught in kilograms was offset by the log transform of the fishing power.

The following model was used:

$$\begin{aligned} \log(\textit{weight offset}) \sim & \textit{year} + \textit{month} + \textit{year:month} + \textit{lunar} + \textit{lunar adv} + \textit{target} + \\ & \log(\textit{hours}) + \log(\textit{fractionopen}) + \textit{random(boat)} + \textit{random(grid)} \end{aligned} \tag{2.2}$$

where:

- repeated variables names are as described above in Equation 2.1,
- $\log($*weight offset*$)$, the response variable, is equal to the log transform of weight of prawns caught in kilograms minus the log of the corresponding fishing power offset (per Section 2.3.3)
- *target* is a binary value representing if tiger prawn were identified as the target species of the fishing trip (per Section 2.3.2)
- $\log($*fractionopen*$)$ is a numerical value representing the log transformed fraction of each compulsory logbooks grid open to fishing in each year to account for the loss of area open to fishing, and
- *random(boat)* and *random(grid)* are fishing boat and fishing grid, included as random effects.

The catch rates were standardised to a modern-day boat. The standardisation factors were:

- *fractionopen* $= 0.3281$ (fraction of grid available to fishing)
- *hours* $= 10.78$ (hours fished)
- *target* $= 1$ (targeting status)
- *lunar* $= 0$ (Luminosity)

- *lunar adv* $= 0.44$ (lunar phase reference)

2.4 Biological relationships

2.4.1 Species split

'Tiger prawn' is a collective term for two species: brown tiger prawn (*Penaeus esculentus*) and grooved tiger prawn (*P. semisulcatus*). Logbook records do not specify if catch is comprised of *Penaeus esculentus*, *P. semisulcatus* or a mix of both, hence tiger prawns must be modeled collectively.

As these species have different biological characteristics and cannot be modeled separately, collective parameters have been determined for use in the model. Biological sampling data *does* differentiate between *Penaeus esculentus* and *P. semisulcatus*. Using these data, a proportion for each species was determined by first filtering biological data to the assessment region (resulting in 43 062 brown tiger prawns and 31 302 grooved tiger prawns). The proportions of brown and grooved tiger prawns in each grid were then calculated, then weighted relative to the catch in each grid, then summed over the entire assessment region. From this, a final overall proportion was calculated, resulting in $P_{\text{brown}} = 0.58$ and $P_{\text{grooved}} = 0.42$.

2.4.2 Fecundity, maturity and proportion of females

The model assumed that tiger prawns recruit into the fishery at 4 months (Somers et al. 1991). The model also assumed tiger prawns reach maturity at 6 months when they were approximately 35 mm (Somers 1987). Prior to this they were considered immature.

No information was available on the fecundity for tiger prawns. For this assessment the number of eggs produced by a female tiger prawn was set to the total weight of mature females.

A monthly spawning pattern vector was sourced from O'Neill et al. (2006b):

$P_{\text{spawning}} = [0.1055, 0.1022, 0.0823, 0.0746, 0.0764, 0.0543, 0.076, 0.088, 0.0789, 0.0965, 0.0808, 0.0847]$

The proportion of males and females in the population were assumed to be equal, hence:

$P_{\text{female}} = P_{\text{male}} = 0.5$.

2.4.3 Weight-length

Fishery models are commonly structured by length (carapace length) whereas commercial fishery catches are measured by weight. Equation 2.3 was used for converting carapace length L, in mm to weight w_L, in grams (Wang 2015).

$$w_L = \alpha L^{\beta} \tag{2.3}$$

Table 2.2: Weight-length parameters for brown and grooved tiger prawns

Parameter	Brown (female)	Brown (male)	Grooved (female)	Grooved (male)
α	0.0026	0.0024	0.002659	0.001955
β	2.67	2.72	2.648	2.746

2.4.4 von Bertalanffy growth

von Bertalanffy growth curve parameters were sourced from Wang (2015). These parameters were based on the relationship:

$$L_a = L_\infty \left(1 - e^{-\kappa(a-t_0)}\right) \tag{2.4}$$

Table 2.3: von Bertalanffy growth parameters for brown and grooved tiger prawns

Parameter	Brown (female)	Brown (male)	Grooved (female)	Grooved (male)
L_∞ (mm)	43.6	34.7	51.64	37.5
t_0 (month)	0	0	0	0
κ (month^{-1})	0.2167	0.2417	0.1863	0.2687

2.4.5 Deriso-Schnute growth

Growth within the population model (Equation 2.5) followed Schnute's extension of the Ford growth equation (Quinn et al. 1999, page 215, Equation 5.14) in which weight at age w_a is a function of weight at age of recruitment w_r, weight at the timestep before recruitment w_{r-1} and the Brody growth cofficient ρ.

$$w_a = w_{r-1} + (w_r - w_{r-1}) \frac{1 - \rho^{1+a-r}}{1 - \rho} \tag{2.5}$$

The parameter ρ was calculated by the following relationship which is a rearrangement of an equation for asymptotic weight derived from Quinn et al. (1999), page 215, Equation 5.14.

$$\rho = 1 - (w_r - w_{r-1}) \,/\, (w_\infty - w_{r-1}) \tag{2.6}$$

Before ρ can be calculated, we must first determine w_∞, w_r and w_{r-1}. These weights at age were determined with the following steps:

1. Find length at age L_a using Equation 2.4 for each species and sex.
2. Find weight at age by substituting L_a into Equation 2.3 for each species and sex.
3. Calculate a collective weight at age (for w_{r-1}, w_r and w_∞) by summing each species and sex weight for a given age multiplied by the sex and species proportions (Equation 2.7). For w_∞ the age chosen is some maximum age value.

$$w_a = P_{\text{brown}} \left(P_{\text{female}} \times w_a^{\text{brown (f)}} + P_{\text{male}} \times w_a^{\text{brown (m)}}\right) + P_{\text{grooved}} \left(P_{\text{female}} \times w_a^{\text{grooved (f)}} + P_{\text{male}} \times w_a^{\text{grooved (m)}}\right) \tag{2.7}$$

Tiger prawns are recruited to the fishery at around $r = 4$ months of age (Section 2.4.2). Resulting growth parameters determined for the model are shown in Table 2.4.

Table 2.4: Deriso-Schnute growth parameters for tiger prawns

Parameter	Value (kg)
w_∞	0.0566
w_{r-1}	0.008
w_r	0.0134
ρ	0.89

2.5 Population model

Several models were developed inside two different modelling frameworks: an internally developed R package called Delay-Difference with User Specified Timestep (DDUST), as well as the publicly available Stock Synthesis tool (version 3.30.17.01). The DDUST implementation builds upon models used and developed in O'Neill et al. (2005), O'Neill et al. (2006b), Courtney et al. (2014a), O'Neill et al. (2014), and Helidoniotis (2021) and a technical description can be found in Appendix F. Stock Synthesis is a richly featured general purpose stock assessment modelling framework and a technical description of Stock Synthesis is given in Methot (2000).

The Stock Synthesis models were unstable and ultimately considered more appropriately reported on only as exploratory work-in-progress (Appendix G). Population model methods and results in the main body of this report relate only to the DDUST models.

2.5.1 Model specification

The DDUST delay-difference population model was fitted to the data to determine the biomass of tiger prawns in each year. The model (Equations 2.8 and 2.9) operated on a monthly time step t:

$$B_t = (1+\rho)s_{t-1}B_{t-1} - \rho s_{t-1}s_{t-2}B_{t-2} - \rho s_{t-1}w_{r-1}R_{t-1} + w_r R_t, \tag{2.8}$$

$$N_t = N_{t-1}s_{t-1} + R_t. \tag{2.9}$$

where B_t was the biomass of tiger prawns (kg), ρ was the Brody growth coefficient, s_t was prawn survival and reflects the combined effects of natural and fishing mortality (a time varying harvest rate defined by $\frac{C_t}{B_t}$), r was the age at recruitment, w_a was the mean weight of prawns at age a (in kg) and R_t was the number of newly recruited prawns. For a technical description of the delay-difference model refer to Appendix F or (Deriso 1980; Hilborn et al. 1992b).

The DDUST modelling framework contains two models which only differ in the treatment of recruitment deviations. The DDUST model, which treats recruitment deviations as fixed effects which contribute to the model likelihood and have a fixed standard deviation of σ_R which must be specified by the user (Maunder et al. 2003). The REDDUST (Random Effect Delay-Difference with User Specified Timestep) model, on the other hand, uses random effect recruitment deviations which are integrated out of the model likelihood and as such, the standard deviation σ_R is able to be estimated soundly by the model. Literature encourages the use of random effect recruitment deviations (Punt 2023) and model analyses found that REDDUST consistently estimated σ_R within a plausible range. For these reasons, REDDUST was used for all delay-difference modelling in this stock assessment except for Scenario 8.

2.5.2 Model assumptions

The main assumptions of the delay-difference model were:

- growth in mean body weight at age is described by the Deriso-Schnute growth (Equation 2.5),
- age at first recruitment to the fishery was at r = four months,
- all animals aged r and older are equally vulnerable to fishing, implying knife-edged selectivity at age r,
- all animals aged r and older have the same annual natural mortality rate,
- all animals aged r and older have the same catchability,
- catch rates were proportional to abundance,
- mean growth function for prawn weight used parameters for both sexes combined,

- there was a 50/50 sex ratio, and
- the stock-recruitment relationship can be described by the Beverton-Holt equation,
- the fishery began from an unfished state in 1958,
- the instantaneous natural mortality rate does not depend on size, age, year or sex.

2.5.3 Model parameters

Natural mortality (M) was fixed at 0.18 per month.

Beverton-Holt stock recruitment steepness (h) was estimated within the model with an informative prior (Table 2.5). Steepness is a metric relating to the productivity of the stock. Specifically, steepness refers to the fraction of recruitment from a virgin population that is obtained when the population is at 20% of virgin biomass (Lee et al. 2012). In the DDUST model, h was reparameterised as ξ using the Equations 2.10 and 2.11.

$$rmax = 1 + \exp(\xi) \tag{2.10}$$

$$h = \frac{rmax}{4 + rmax} \tag{2.11}$$

Catchability was assumed to follow a seasonal cycle. This seasonal cycle was captured using Equation 2.12 where parameters q_1 and q_2 were estimated in the model. The parameter $log(q_{\text{base}})$ is defined in Appendix F.

$$q_t = \exp\left(log(q_{\text{base}}) + q_1 \cos\left(\frac{2\pi t}{12}\right) + q_2 \sin\left(\frac{2\pi t}{12}\right)\right). \tag{2.12}$$

The DDUST package has the capacity for intra-annual patterns of spawning and recruitment, which were also assumed to follow a seasonal cycle. The spawning pattern indicates the proportion of the adult female population spawning during each month and must be specified by the user. The recruitment pattern indicates how the recruits are distributed among the year and is governed by two parameters k and μ which were estimated by the model with informative priors (Table 2.5). The monthly recruitment pattern (ϕ_t) is assumed to follow an exponential cosine function:

$$\phi_t = \frac{\exp\left(k\cos(t-\mu)\frac{2\pi}{12}\right)}{\sum_{t'=1}^{12} \exp\left(k\cos(t'-\mu)\frac{2\pi}{12}\right)}, \qquad t \in \{1, \ldots, 12\}. \tag{2.13}$$

Due to the cyclic nature of the cosine function, the parameters k and μ may produce the exact same pattern at different fixed values. Both the spawning pattern and recruitment pattern are converted to the appropriate time step by summing the proportions in adjacent months as illustrated in Figure F.1.

The DDUST model estimated R_{init} which can be transformed to initial recruitment according to the form:

$$R_0 = \exp(R_{\text{init}}) \cdot R_{\text{scalar}} \tag{2.14}$$

where R_{scalar} is a value used for recruitment parameter transformation. For this assessment, $R_{\text{scalar}} = 1$ and hence $R_{\text{init}} = \ln(R_0)$.

Parameters for the log transformed variance of recruitment ($\log(\sigma_R)$) and log transformed variance of abundance index ($\log(\sigma_I)$) were also estimated within the model.

Recruitment deviations between 1988 and 2021 were estimated within the model as random effects.

The parameters ξ, k and μ were given priors. These priors and their associated standard deviations and prior types are displayed in Table 2.5.

Table 2.5: Model parameters with associated priors, prior standard deviations and prior types

Parameter	Prior	Prior SD	Prior Type
ξ	log(3)	1	Normal
k	5	100	Normal
μ	5	100	Normal

2.5.4 Parameter estimation

A Markov chain Monte Carlo (MCMC) was performed on all scenarios using 10 000 iterations (5000 warm-up) and 5 chains to investigate the posterior parameter distributions defined by DDUST. MCMC was run using the *tmbstan* package (**tmbstan**) which enables Stan (**stan**) functionality for a TMB model object. Convergence of the MCMC was monitored using the potential scale reduction factor ($\hat{R}$) (Brooks et al. 1998) and visual examination of the posterior densities, trace plots and correlation plots (see Appendix B.1). Success was determined for values $0.99 < \hat{R} < 1.01$ (Gelman et al. 2013), overlapping posterior density between chains and mixing of chains in the trace plot. MCMC results were used to report biomass estimates with associated uncertainty. A single representative biomass point estimate was defined as the median final biomass. Most diagnostic plots pertain to the trajectory associated with the median sample e.g., Figure B.34.

The model parameters were also estimated using the general-purpose function *optim* based on a quasi-Newton algorithm. The results from this maximum likelihood estimation (MLE) approach are shown for comparison in Figures B.2–B.11.

As this report uses both MCMC and MLE it is important to distinguish how uncertainty is reported in both situations. The Bayesian term 'credible interval' reflects that there is a 95% probability that the parameter or quantity is within that interval, conditional on the data and the model. Alternatively, maximum likelihood methods use the frequentist term 'confidence interval' to describe the interval in which the parameter or quantity would be within for 95% of the possible realisations of error. Confusingly, both are condensed to the acronym 'CI' but should be distinguishable by context.

2.5.5 Sensitivity tests

A number of additional model runs were undertaken to determine the model's sensitivity to fixed parameters, assumptions and model inputs. The sensitivities, and notations used to denote variations, were as follows:

- **Catch rates:** Changes in marine park zoning over time, and subsequent limitations to trawling, could influence the estimate of biomass if not suitably captured in the model. Although the fraction of available fishing area (which decreased through time) was captured as a covariate in the catch rate standardization model, further scenarios were tested to explore the effect of zoning changes.
  - Continuous: Catch rates modelled as one continuous time series, unchanged from the standardisation model
  - Offset: Catch rates were manually offset by 10% for each of the three periods between zoning changes: post-2004 catch rates remained unchanged, 1986–2004 catch rates were multiplied by 0.9, and pre-1986 catch rates were multiplied by 0.81. The size of the offset (10%) was

determined using the decrease in harvest as a proxy for the artificial decrease in catch rates, in lieu of more informative data. Hand (2003) and analysis of high resolution vessel tracking data indicated that harvest in the fishery reduced by 6% as a result of the spatial closures. A conservative offset of 10% was used as a sensitivity test.
  - Split: Catch rates were split into three separate time series (pre-1986, 1986–2004 and post-2004), allowing the model to calculate a catchability coefficient for each time series

- **Historical retained catch data:** Prior to the introduction of daily logbooks in 1988, retained catch data were collected from the commercial sector via the Queensland FishBoard, and estimated in Hutchison (2015). It is assumed that not all prawns were sold through the Queensland FishBoard and that the information from Hutchison (2015) may not have captured the entirety of the fishery. As such, commercial retained catch data collected in this period may be an underestimate. As a sensitivity test, a multiplier was applied to the Queensland FishBoard retained catch data in a number of scenarios.
  - 150%: historical retained catch data multiplied by 1.5
  - 75%: historical retained catch data multiplied by 0.75
  - 100%: historical retained catch data used as reported
  - 200%: historical retained catch data multiplied by 2

- **Model choice:** The package 'DDUST' contains two different model types (DDUST and REDDUST). Deviations from the annual recruitment R_t were treated as fixed effects in DDUST and random effects in REDDUST by integrating the recruitment parameters out of the likelihood. Treating the parameters as random effects reduces the direct influence of recruitment deviations on the model likelihood. Under this framework, recruitment deviation parameters are random samples from a normal distribution with mean 0 and variance σ_R^2. There is no condition that forces the recruitment deviation samples to have a sample mean of 0.
  - REDDUST: Recruitment deviations were treated as random effects.
  - DDUST: Recruitment deviations were treated as fixed effects.

- **Recruitment deviations start year:** Initial model runs used a start year of 1988 for recruitment deviation estimation. This was based on the earliest influence of catch rates sourced from compulsory logbooks. Due to the strong influence of recruitment deviations on overall stock status estimated, the model was also tested with recruitment deviations starting at 1970, representing the start of HTRAWL (historic voluntary) catch rates. It should be noted that the catch rates from HTRAWL data had a greater degree of uncertainty around them.
  - 1988, the start of compulsory catch rates
  - 1970, the start of historic voluntary catch rates

- **HTRAWL:** The voluntary nature of the HTRAWL data raised questions about their appropriateness to be included in the model, so scenarois were run with the data included and excluded from the data inputs.
  - Yes: Catch rates derived from HTRAWL data are included in the model
  - No: Catch rates derived from HTRAWL data are not included in the model

Ten combinations of sensitivities were tested, as outlined in Table 2.6. The project team's preferred scenario has been named Scenario 1. Other scenarios are numbered in a methodical order based on different parameter settings and do not represent a rank of plausibility.

Table 2.6: Scenarios tested to determine sensitivity to parameters, assumptions and model inputs for east coast tiger prawns—scenario 1 is the project team preferred scenario

Scenario	Catch rates	Historical retained catch data	Model choice	Recruitment deviations start year	HTRAWL
1	Continuous	150%	REDDUST	1988	Yes
2	Offset	150%	REDDUST	1988	Yes
3	Split	150%	REDDUST	1988	Yes
4	Continuous	75%	REDDUST	1988	Yes
5	Continuous	100%	REDDUST	1988	Yes
6	Continuous	125%	REDDUST	1988	Yes
7	Continuous	200%	REDDUST	1988	Yes
8	Continuous	150%	DDUST	1988	Yes
9	Continuous	150%	REDDUST	1970	Yes
10	Continuous	150%	REDDUST	1988	No

The model inputs that comprise the project team preferred scenario were chosen by the project team before biomass trajectories were presented to remove preconceived ideas about the tiger prawn stocks.

The project team decided that continuous catch rates with the inclusion of catch rates derived from HTRAWL data was an appropriate representation of the fishery was preferred. Scenarios testing the sensitivity to offset and split catch rates and also the inclusion of HTRAWL catch rates were also tested.

The historical harvest reconstruction used a suite of data sources including Queensland Fishboard data, Hutchison (2015) and compulsory commercial logbooks. The resulting reconstruction was considered too low by the project team for the historical portion but was accepted with 1.5 times the historical portion. Other weightings of the historical portion of the harvests were sensitivity tested (refer to Section 2.2.2 for more information).

After reviewing model fits and diagnostics from the DDUST and REDDUST models, the project team selected the REDDUST model as the favoured option. A scenario with the DDUST model used was tested as a scenario. Additionally, model fits and diagnostics were also reviewed for the recruitment deviations start year and the start of compulsory logbooks (1988) was chosen by the project team as preferred. A scenario where the recruitment deviations started at the start of the HTRAWL data was also tested.

3 Results

Model inputs are described for tiger prawns. Model outputs relate to Scenario 1 as defined in Table 2.6. Results from all other scenarios are presented in Appendix B.

3.1 Model inputs

3.1.1 Data availability

Figure 3.1 summarise the assembled data sets input to the model for the tiger prawn project team preferred model.

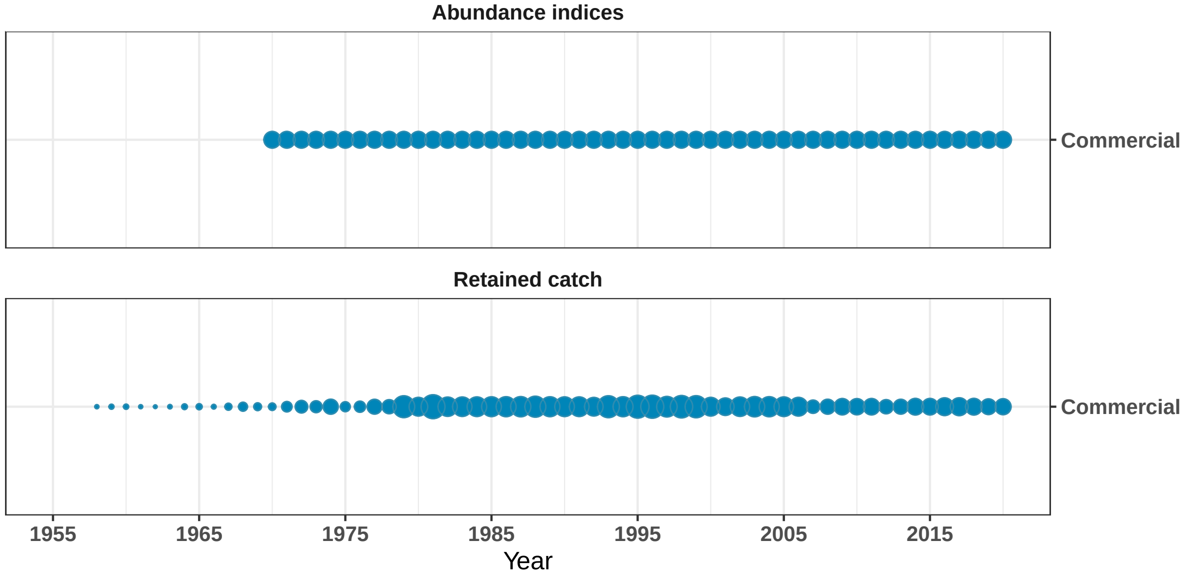

Figure 3.1: Data presence by year for each category of data type for tiger prawns

3.1.2 Retained catch estimates

Total annual and monthly retained catch from the commercial sector is shown in Figures 3.2 and 3.3, respectively. The magnitude of recreational, charter and Indigenous harvests were not considered significant for tiger prawns. The retained catch of tiger prawns peaked in 1981 at 2654 t. Over the last 5 years (2017–2021) total retained catch averaged 1098 t per year.

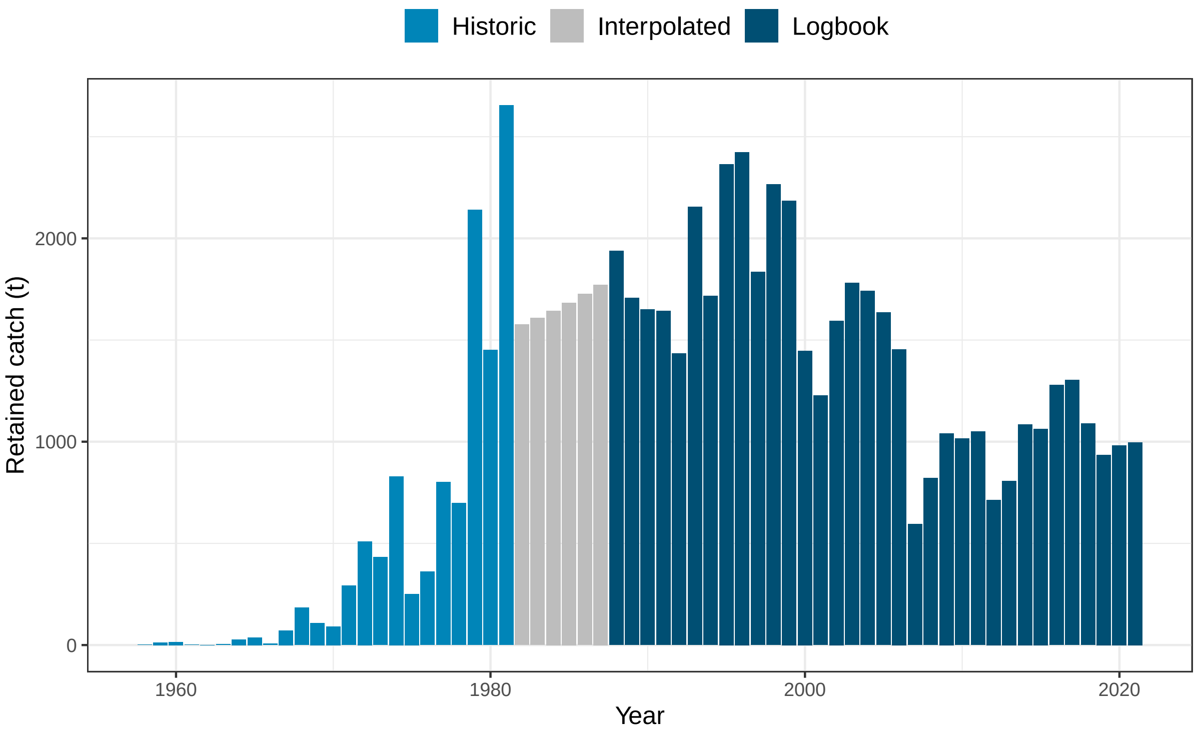

Figure 3.2: Annual estimated retained catch between 1985 to 2021 for east coast tiger prawns for the project team preferred scenario

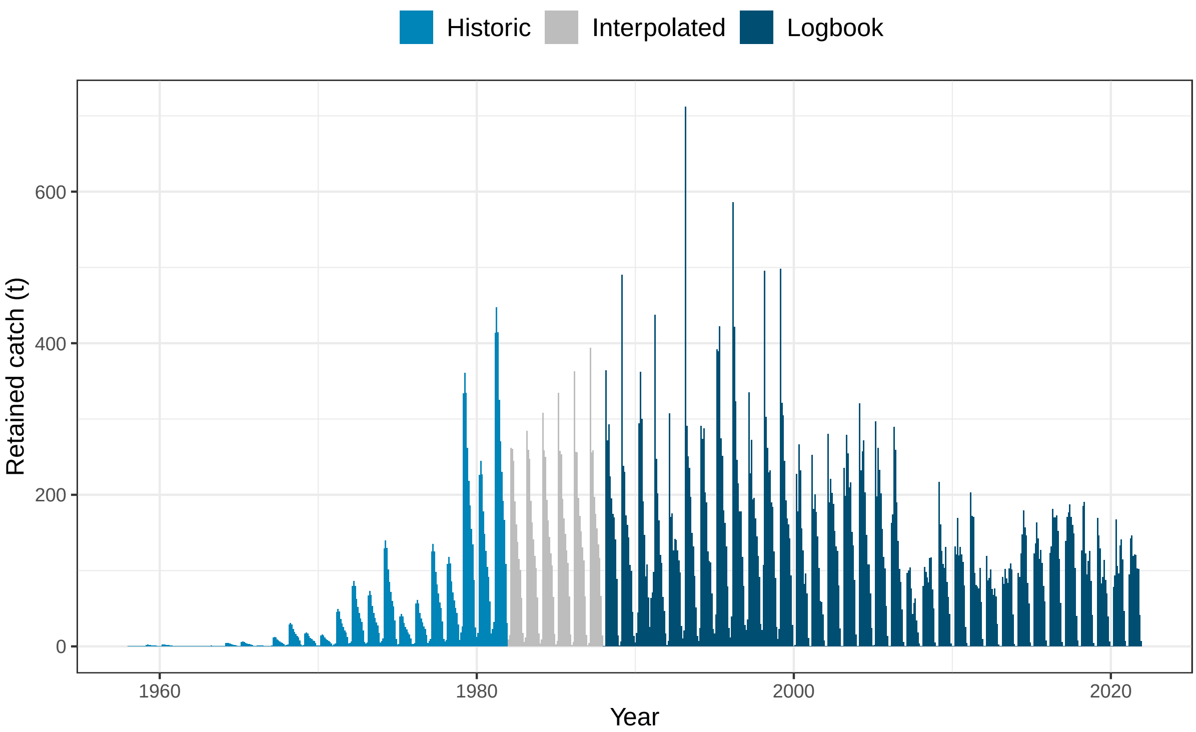

Figure 3.3: Monthly estimated retained catch between 1985 to 2021 for east coast tiger prawns for the project team preferred scenario

3.1.3 Standardised indices of abundance

A rising trend in both the monthly and annual standardised catch rates for tiger prawn since approximately 1985 is displayed in Figures 3.4 and 3.5. The catch rate trends show considerably higher catch rates for those assoiciated with HTRAWL data, particularly between 1975 and 1979, with larger confidence bands around these estimates.

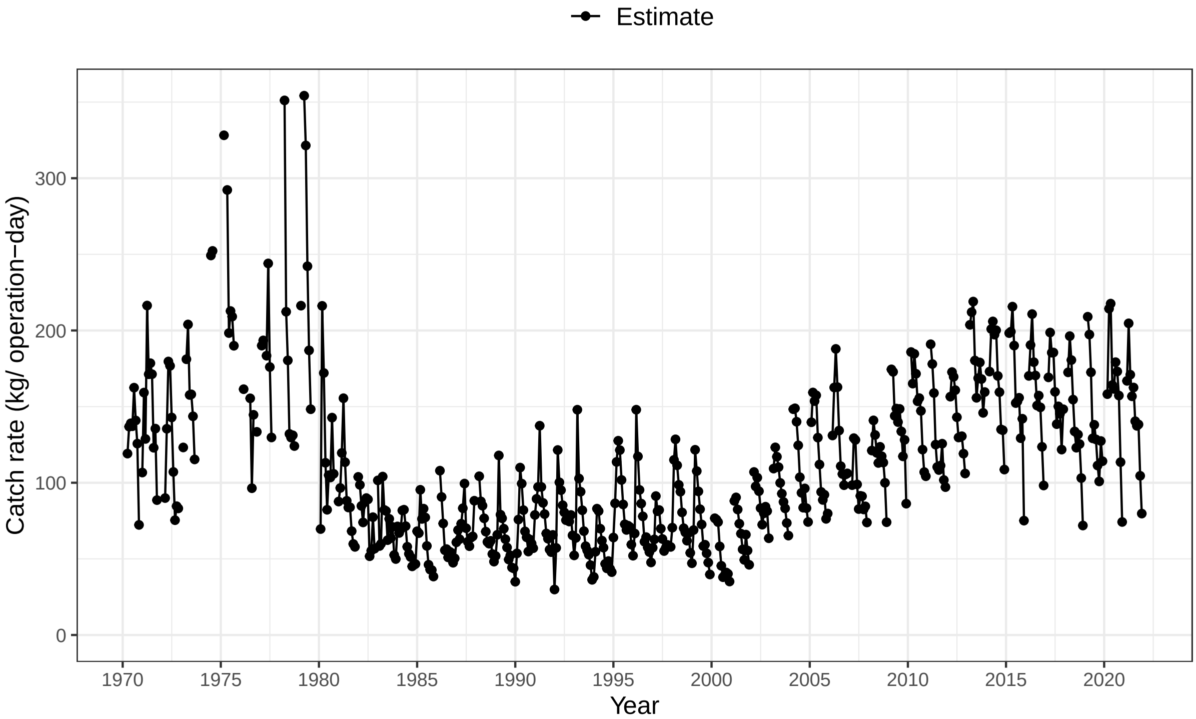

Figure 3.4: Standardised catch rates for tiger prawns between the years of 1970 and 2021

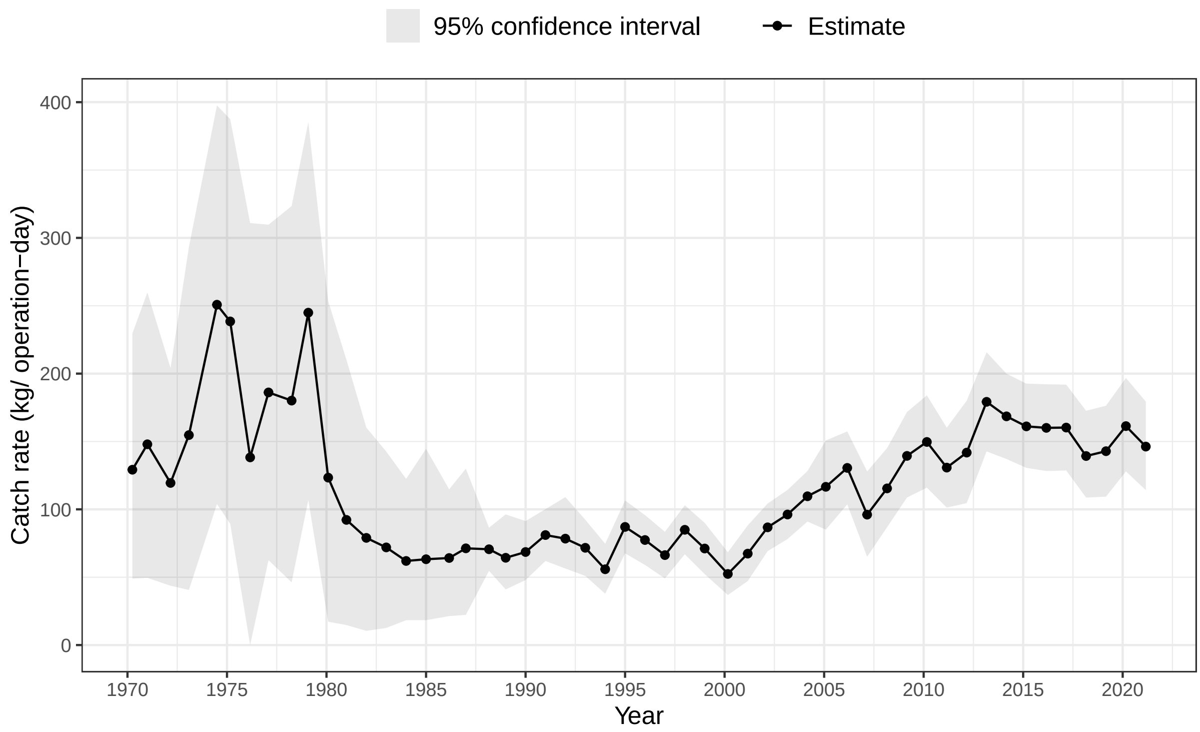

Figure 3.5: Annual standardised catch rates for Queensland commercial tiger prawns between 1970 and 2021

Fishing power analysis results and further catch rate standardisation model results are in Appendix A.1.

3.1.4 Other model inputs

Other model inputs such as fixed biological relationships are provided in Appendix A.

3.2 Model outputs

Note, the Bayesian term ‘credible interval’ reflects that there is a 95% probability that the parameter or quantity is within that interval, conditional on the data and the model. Alternatively, maximum likelihood methods use the frequentist term ‘confidence interval’ to describe the interval in which the parameter or quantity would be within for 95% of the possible realisations of error. In the summary of this report we use the term ‘uncertainty interval’ to describe a credible interval for ease of interpretation without distinguishing between frequentist and Bayesian methods.

3.2.1 Model parameters

A number of parameters were estimated within the tiger prawn population models (Table 3.1). The posterior distributions of estimated parameters for each of the model scenarios can be found in Appendix B.1.

Table 3.1: Summary of parameter estimates from the base population model—2.5%, Median and 97.5% columns correspond to MCMC percentiles and the Median B_{2021} column is the parameter value of the trajectory corresponding to a median biomass in 2021

Parameter	Fixed	Median B_{2021}	2.5%	Median	97.5%
h	–	0.44	0.4	0.44	0.49
$\ln(R_0)$	–	19.23	19.15	19.22	19.3
k	–	0.65	0.31	0.58	0.93
μ	–	2.34	0.36	1.75	2.73
q_1	–	-0.05	-0.19	-0.1	-0.01
q_2	–	0.06	-0.02	0.08	0.18
$\ln(\sigma_I^2)$	–	-2.77	-2.99	-2.84	-2.69
$\ln(\sigma_R^2)$	–	-3.34	-4.04	-3.45	-2.81
M	0.18	–	–	–	–

3.2.2 Model fits

Good fits were achieved for the tiger prawn project team preferred scenario. MCMC diagnostics (see Appendix B.1) indicate that scenarios 1, 2, 4, 5, 6, 7, and 10 have a high probability of convergence for tiger prawn. Scenario outputs of scenarios with a high probability of convergence are presented in Appendix B.2.

3.2.3 Biomass

Ten model scenarios were run for the tiger prawn stock, covering a range of modelling assumptions and sensitivity tests. The tiger prawn project team preferred model predicted stock biomass declined between 1958 and 1996 to reach 31% of unfished biomass. The biomass has been steadily rising since this time, with the stock level estimated to be 79% (70–89% credible interval) of unfished biomass at the beginning of 2022 (Figure 3.6). Relative biomass trajectories for all sensitivity scenarios are presented in Figure 3.7. In general, all scenarios—aside from Scenario 9—followed a similar trend to the project team preferred scenario. Scenario 9, in which recruitment deviations started in 1970 showed high correlation between the calculated recruitment deviations and the biomass trajectory, resulting in an unrealistic biomass increase in the 1980s. Scenario 3, in which the the catch rates were split into fleets that correspond with changes to available fishing zones, showed a more pessimistic biomass trajectory.

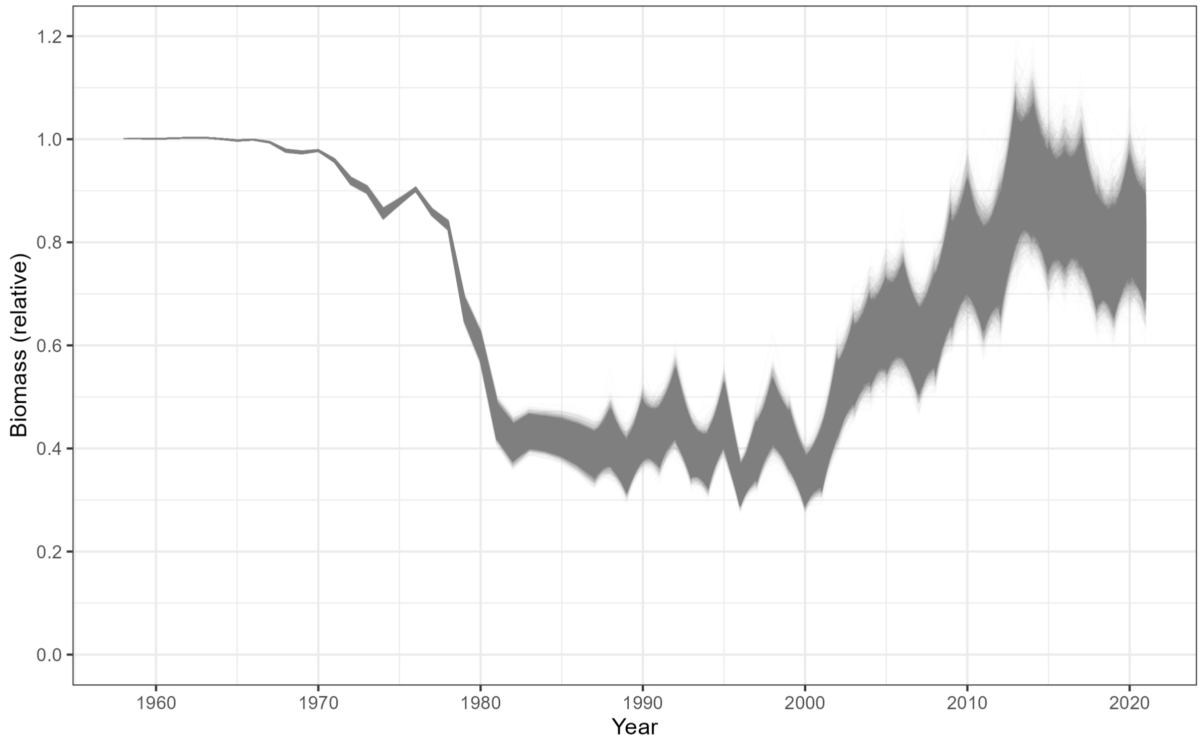

Figure 3.6: Predicted biomass trajectory relative to unfished for tiger prawns, from 1958 to 2021—grey lines represent individual MCMC samples

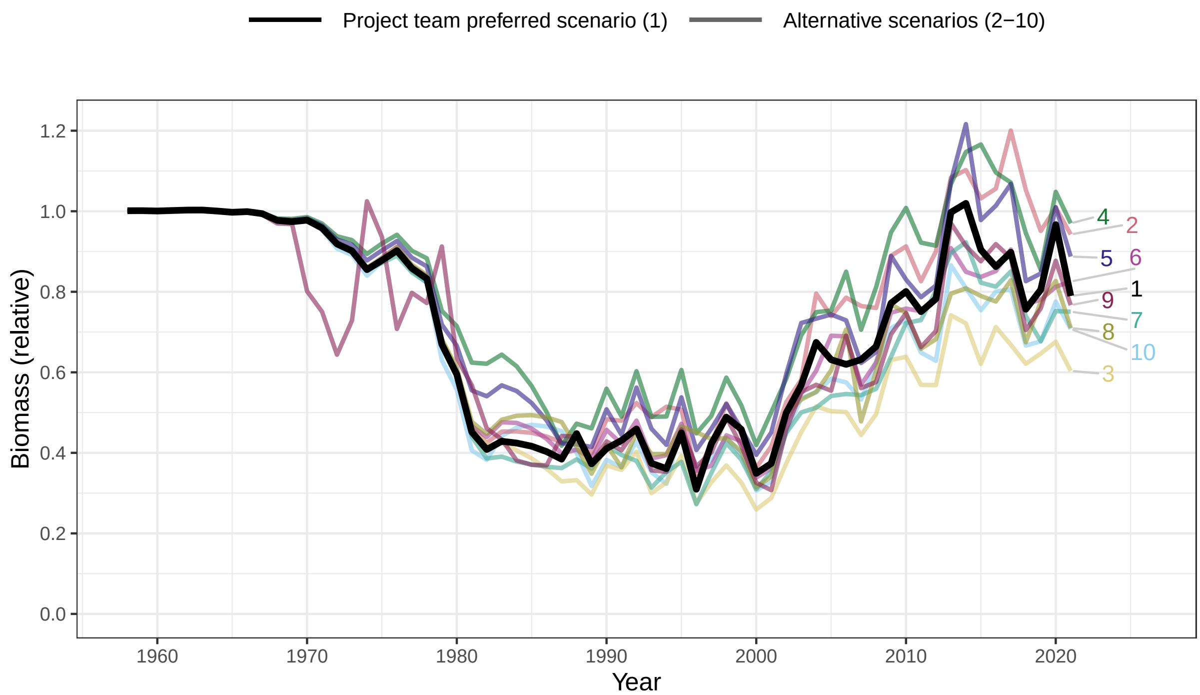

Figure 3.7: Range of predicted biomass trajectories relative to unfished for tiger prawn, from 1958 to 2021, for all scenarios—the project team preferred scenario is scenario 1

While the biomass ratio provides an indication of where the stock is, the fishing pressure in the last year of the model gives an indication of where the biomass is heading. The combination of biomass level and biomass direction provides a more complete picture of stock status (Table 3.2). Subject to current fishing pressure, the tiger prawn stock biomass is decreasing in scenario 1 (project team preferred).

Table 3.2: Stock status indicators for east coast tiger prawns in 2021

Indicator	Estimate
Biomass (relative to unfished)	79% (70–89% credible interval)
Biomass direction	Decreasing
Catch	997 t

Stock status indicators for all scenarios, along with model convergence and biological plausibility are presented in Table 3.3).

For model outputs pertaining to maximum sustainable yield and stock status, refer to Appendix B.2.

Table 3.3: Summary of model outcomes for all tiger prawn scenarios—B_{2021} % is the most likely biomass in 2021 relative to unfished in 1968 with the 95 % credible interval (CI)

Scenario[†]	MCMC					MLE		Biological
	$B_{2021}\%(CI)$	$MSY(t)$	$B_{MSY}\%$	$-\ln L$	$\rightarrow\leftarrow$	$-\ln L$	$\rightarrow\leftarrow$	Plausibility
1 ***a***	79 (70–89)	1520	35	-525	TRUE	-448	TRUE	TRUE
2 ***a***	94 (83–107)	1583	34	-507	TRUE	-430	TRUE	TRUE
3	60 (44–78)	1389	38	-538	TRUE	-469	TRUE	TRUE
4 ***a***	97 (85–111)	1384	27	-482	TRUE	-424	TRUE	TRUE
5 ***a***	89 (78–101)	1398	31	-520	TRUE	-445	TRUE	TRUE
6 ***a***	83 (73–94)	1477	32	-520	TRUE	-453	TRUE	TRUE
7 ***a***	75 (66–86)	1657	39	-516	TRUE	-417	TRUE	TRUE
8	71 (63–81)	1809	33	-525	TRUE	-532	TRUE	TRUE
9	77 (67–87)	1820	26	-631	TRUE	-558	TRUE	TRUE
10	71 (61–81)	1748	30	-520	TRUE	-420	TRUE	TRUE
Ensemble⋆	79 (54–104)	–	–	–	–	–	–	

⋆ the ensemble model summarises all MCMC iterations across the scenarios

[†] log-likelihood ($-\ln L$) values that are comparable contain identical superscripts (***a***) and lower values for the comparable likelihoods are indicative of a better fit

CI 95% credible interval

$\rightarrow\leftarrow$ high probability of model convergence

Biological Plausibility: This column highlights scenarios with large jumps in biomass within a year or two—these scenarios were deemed ‘not plausible’ and given a rating of FALSE

4 Discussion

4.1 Stock status

This assessment was an update to Helidoniotis (2021) which estimated the east coast tiger prawn stock to be approximately 50% of unfished biomass. This assessment predicted biomass to have increased from 31% of unfished biomass in 1996 to reach 79% of unfished biomass (70–89% range across the 95% credible interval) at the end of 2021. This difference in final biomass predictions has been explored thoroughly via a bridging analysis in Appendix E.

The biomass trend showed four general phases: a period of decline between 1958 and 1982, a steady period between 1982 and 2000, then a period of increase from 2000 until 2014, then a period of decrease from 2014 onwards. The trend from 1982 onwards corresponds with the trend seen in the catch rate time series (Figure 3.5) for catch rates associated with compulsory logbook data.

The initial period of biomass decline seen from 1958 and 1982 was characterised by increased retained catch over time and recruitment deviations. There were no fishery management measures in place, with no abundance indices to inform early biomass trajectory.

Note that not only the project team preferred outputs but the full range of outputs across scenarios should be considered when interpreting the assessment.

4.2 Performance of the population model

The population models were optimised using the MLE approach foremost and then the MCMC approach in order to better explore the robustness of the models. The project team preferred scenario performed well under both optimisation methods and resulted in a biologically plausible biomass trajectory with a high probability of convergence. The MCMC optimisation method found a slightly better fit (lower negative log likelihood) for the project team preferred scenario when compared to the MLE method. All of the sensitivity scenarios resulted in biologically plausible biomass trajectories with a high probability of convergence.

Scenario 1 was chosen by the project team as the preferred model, however other scenarios were also considered plausible. This is best understood by considering the following key contributors to the overall uncertainty:

- **Using catch rates to represent fishery closures.** The effect of the treatment of the catch rates on the outcome of the population model can best be seen in Appendix A.1. In Scenario 3 (split catch rates), the calculated catchability coefficient resulted in the model interpreting the catch rates as less resilient than in the project team preferred scenario. Applying the manual catch rate offset resulted in more optimistic catch rates.
- **Historical retained catch data.** Five different scenarios pertaining to the historical retained catch data were run; rescaling retained catch prior to 1988 by 75%, 100%, 125%, 150% and 200% in Scenarios 4, 5, 6, 1 and 7 respectively. As the historic retained catch was scaled up (towards 200%), the final relative biomass estimate decreased and the initial estimate of recruitment increased. This is an intuitive response, as the earlier period was modelled to experience higher fishing pressure and the model responded by estimating a higher carrying capacity of the stock.

- **REDDUST vs DDUST.** Scenario 8 used the DDUST model instead of REDDUST; in which recruitment deviations were estimated as fixed parameters rather than random effects. Overall the final biomass trajectory, catch rate fits and parameter estimates were similar to the project team preferred model.
- **Recruitment deviations start year.** Two different scenarios pertaining to the starting year of recruitment deviations were run: the base, beginning in 1988 (based on the influence of compulsory logbook catch rates upon spawner-recruitment) and the alternative, beginning in 1970 (based on the inclusion of HTRAWL catch rate data).
- **Inclusion of HTRAWL.** Scenario 10 excluded the catch rates derived from HTRAWL data (historic voluntary logbooks) from the model inputs. This scenario resulted in a lower biomass trajectory than the project team preferred scenario.

4.2.1 Stock Synthesis

Stock Synthesis is a more richly featured modelling framework than DDUST, and provides the ability to incorporate length frequency data, explicitly model growth, handle selectivity by fleet, length at maturity, and consider minimum legal size changes. However it can be challenging to apply for short-lived hard to age species like tiger prawns. The Stock Synthesis models had difficulty converging or were highly sensitive to small changes in inputs. Further work may resolve these difficulties, but at this stage the lack of robustness suggests these analyses should be considered preliminary and exploratory only. Because they may prove useful in future, and because they do contribute to the overall understanding in terms of data needs and model sensitivities, the results are being made available and can be accessed in Appendix G.

4.3 Unmodelled influences

There are a number of potential drivers of the east coast tiger prawn population that have not been directly modelled, but should be taken into consideration when interpreting model outputs and considering future assessments or management arrangements. These include environmental variables and fishing power changes. These influences are discussed below.

- **Environmental variables.** Environmental variables such as wind, cyclones, rainfall, and tides could be drivers of tiger prawn abundance; none of which were included as variables in the catch rate standardisation or in the stock assessment model as environmental parameters. Tidal effects may be linked to the lunar descriptors which were included in the standardsiation, however further analysis is required to determine how strong the correlation is. Industry feedback suggests that catch rates in some areas of the east coast are more influenced by tides than others, so a combination of tide and region may be investigated.
- **Day-night effect.** Tiger prawns often exhibit different behaviour during the day than at night (Kienzle et al. 2014). There have been parts of the history of the fishery where some areas were closed during the day after having been open to fishing for many years. Industry feedback suggests that catch rates can be higher during the day for some parts of the year, whilst during other times of the year better catch rates occur at night. This may suggest the potential need for an interaction between area, month, and day versus night in the catch rate standardisation, as well as the occurance of daylight closures within the fishery. Further analysis of the proportion of fishing day occuring during daylight hours, and the variation of this through the year, could be conducted.
- **Skipper experience/quality.** The catch rate standardisation incorporates different boat marks, which to some extent reflects differing experience across the fleet, however further work could be

done to categorise the experience of a skipper which could be used to standardise catch rates. This raises the question of how skipper experience could be quantified. The number of years experience does not necessarily mean they are a better fisher; work ethic and natural talent also contribute to the performance and development of a skipper. Potential analysis could be conducted on the catch rates associated with each skipper over time could be explored as a way of categorising skipper quality. Logbook data identifying the skipper are available from 1988 onwards, so information on skipper experience before then would need to be assumed or hindcast.

4.4 Recommendations

4.4.1 Research and monitoring

The following recommendations for tiger prawns are made to reduce model uncertainty and address key assumptions:

- **Trawl catch rates.** A broader scoped analysis on catch rates for the East Coast Otter Trawl Fishery has been flagged as an important body of work, as opposed to analysing catch rates on a per-species basis. This will allow for a more thorough exploration on spatial structure, inter-species interactions and environmental drivers.
- **Species split.** Although work was done in this assessment to identify 'tiger prawn' catch records as either brown or grooved tiger prawns (per Section 2.4), further work could be done to improve this species split, using similar methodology as Venables et al. (2006) which was supported by fine scale data. Compulsory logbooks have recently (as of September 2021) started recording species split between brown and grooved tiger prawns, and this data could be used to support further work in identifying between the two species.
- **Validation of gear data.** Further work could be conducted to validate the historic gear data used to analyse fishing power.
- **Justification of voluntary catch and effort data.** Further work could be conducted to improve the uncertainty in the historic catch and effort data used in the standardised catch rate model. The high magnitude of catch rates from these data raises concerns that there may be potential bias or over reporting present in the data set, however the data come from 15 different data sources which aids in justifying its validity. Comparisons of the nominal catch rates of fishers present in both HTRAWL and compulsory logbook data sets showed that reporting was relatively consistent between the two data sets. After applying data filters described in Section 2.3.1, 182 unique ACNs reported catch of tiger prawns in the HTRAWL data set, 714 in the compulsory logbook data set, and 128 were common to both data sets. This implied a degree of continuity between the two data sets, which helped to justify the use of the HTRAWL data. Additional research in this space could further validate the use of these data.
- **Catchability.** Scenario 3 allowed catchability to be split into three segments (i.e., for each major rezoning of the fishery area) with catchability estimated separately for each period. Splitting catch rates for each time period was incorporated as a modelling option allowing the model to estimate how catchability had likely decreased from areas lost to trawling as a result of each closure. Future research should aim to explore if catchability has increased or decreased as a result of rezoning or if other factors are at play (i.e., increased targeting, less efficient fishers leaving the fishery) as mentioned in the discussion.
- **Emergence of mother-shipping.** The impact of the emergence mother-shipping is complicated, even from a data gathering perspective and has been noted for future work.

- **Variance in biological information.** Most biological information, such as growth and seasonality in reproduction is based on literature values. This information was included in the model without variation. The inclusion of variance in biological information could be explored in future work, however the effects of this might be marginal compared with the variation arising among the different scenarios.

4.4.2 Assessment

Future assessments could be improved by:

- **Assessing the validity of the dynamic pool assumption.** Industry feedback suggests the spatial closures within the fishery, in 1986 and 2004, had a major impact on the fishery that would artificially bias the catch rates and cause them to misrepresent potential local depletion. The suitability of how these closures were handled are a major source of uncertainty within the stock assessment. Scenarios 1–3 represent attempts to model potentially higher availability of tiger prawns in regions which were closed to trawling. Allowances were made in the catch rate model as a way of representing the index of abundance of the whole population; regardless of zoning status. It is possible that additional spatial closures through the history of the fishery may have influenced the final stock status, and these could be considered in future assessments.

  Scenario 2 saw a manual readjustment of the catch rates to account for any impact due to existing spatial inhomogeneity, assuming an artificial bias of 10% for each major closure (in 2004 and 1986). The magnitude of this scaling factor (10%) is difficult to justify without fishery independent survey data. Work done by Hand (2003) paired with high resolution vessel tracking data suggested a 6% loss in harvest as a result of the 2004 closure, which closed off 30% of the Great Barrier Reef Marine Park to trawling. Neither of these values are indicative of the artificial bias presented in the catch rates. A small survey was done as a part of this stock assessment to gather data from industry members on the effects of the closures on catch rates, however the resulting data were not suitable for use in the population model.

  The influence of the spatial closures is in conflict with the dynamic pool assumption made for this assessment, in which all prawns with the stock are perfectly mixed closed units, without spatial variation, and with reproductive connectivity. If the dynamic pool assumption does hold, and spatial homogeneity is assumed, then catch rates in the open area are representative of the population. Evidence suggests the distribution of tiger prawns is dependent on sediment type and the 2004 rezoning of the Great Barrier Reef Marine Park considered equal removal of habitat types, meaning not all of the 30% of area removed from trawlable fishing ground was suitable habitat for tiger prawns. Tiger prawns are relatively sedentary, so the dynamic pool assumption might be applied. The project team preferred model (Scenario 1), in which catch rates remain continuous, retains the dynamic pool assumption.

  Further complexity is added to the issue when considering the behaviour of fishers as they respond to managerial changes within the fishery; shifting the focus and strategy of their fishing operations. Data are not available to suitably model this phenomenon.

  Modelling work was done in this assessment to explore an explicit spatial, seasonal model using the Stock Synthesis modelling framework (Appendix G). This model explored the use of fleets to represent the areas defined in Figure 2.1, which controlled the level of mixing between fleets. Unfortunately, the data available did not support the complexity of such a model.

- **Reviewing fleet structure.** A repeat assessment should reconsider the fleet structure of the model, potentially separating catch rates from different data sources (HTRAWL vs compulsory logbook) as well as catch rates for different periods of spatial zoning (as in Scenario 3 in the current assessment). Available data sets might not support this level of model complexity.
- **Seasonal selectivity.** Future work should aim to incorporate monthly catchability into Stock Synthesis models as per the REDDUST model. Monthly patterns of catchability were reported for tiger prawns from the REDDUST models. This could be implemented by assigning a fleet structure wherein twelve fleets are used to represent each of the months (i.e., January, February, etc).
- **Seasonal recruitment.** As with many crustaceans, tiger prawns are relatively short-lived. Consequently, much of their biology and population dynamics likely occur on a monthly time scale (i.e., spawning and recruitment). Stock Synthesis can be configured to distribute recruitment throughout the year, termed seasonal recruitment. For the current assessment, seasonal recruitment was estimated for the Stock Synthesis model. However, using the recommended settings as per the Stock Synthesis User Manual 3.30.20 (Methot et al. 2022), seasonal recruitment parameters hit bounds and did not estimate cleanly. For the monthly Stock Synthesis models presented, to obtain clean parameter estimates the parameter bounds were sixteen times that of the recommended values from the Stock Synthesis User Manual. The requirement for parameter bounds sixteen times the recommended values formed part of the weight of evidence to not present the monthly Stock Synthesis models to the project team.
- **Stock Synthesis modelling.** Future assessments should continue to experiment with Stock Synthesis to assess tiger prawns. Stock Synthesis has the ability to incorporate length- and age-based data (if age data were available for tiger prawns). The incorporation of length-based data allows a number of processes to be estimated including selectivity, discarding, minimum legal size and sex-specific growth. Increasing the model weighting of length compositions could improve model performance. Using a pre-specified growth curve, length data can also be converted into age data to analyse cohorts. When understood in the future, environmental links to tiger prawn population dynamics can also be modelled using Stock Synthesis.
- **Sex-specific growth.** Female tiger prawns grow larger than males. In the current REDDUST model used for this assessment, tiger prawns were modelled as a single-sex population. Future assessments should aim to model sex-specific growth to more accurately represent the biology of tiger prawns.
- **Selectivity.** Another effect of sex-specific growth for tiger prawns are differences in selectivity and thus, vulnerability to the fishery. As females reach larger sizes than males, females are exposed to fishing before, and potentially more so, than males. Differences in selectivity due to sex-specific growth and gear types should be considered in future assessments when length information can be incorporated into modelling.
- **Length data.** A time series of fishery dependent length frequency data is available for the east coast tiger prawn population (Fisheries Queensland 2012b), however length data cannot be incorporated into current REDDUST modelling. Future efforts should focus on achieving a plausible outcome from an analysis that can incorporate length frequency data such as Stock Synthesis.

4.5 Conclusions

This assessment was commissioned to establish the status of Queensland's east coast tiger prawn stock and inform the management of the East Coast Otter Trawl Fishery. The project team preferred scenario suggested current biomass (compared to unfished levels) for the stock is around 70–89%. Some recommendations for future work have been made.

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Appendix A Model inputs

A.1 Abundance indices

Scenarios 1–3 represent different approaches to capturing the effect of fishery management changes that resulted in decreased area available to fishing, as described in Section 2.5.5.

For the project team preferred scenario, catch rates were input into the model as one fleet, with a constant catchability calculated for the entire time series. In Scenario 3, the catch rates were input to the model as three independent time series, representing periods of time between spatial zoning changes in which the area available to fishing was reduced, each of which had a constant catchability coefficient calculated. In Scenario 2, catch rates were input to the model as a continuous time series with a manual offset. A constant catchability was calculated for the entire time series.

Figure A.1 shows each catch rate time series (for Scenarios 1–3) divided by its respective catchability coefficient, then multiplied by the catchability coefficient of Scenario 1, to demonstrate the effective catch rates as imposed by calculated catchability coefficient and allow for comparison between scenarios. The implications of this effect are discussed in Section 4.2.

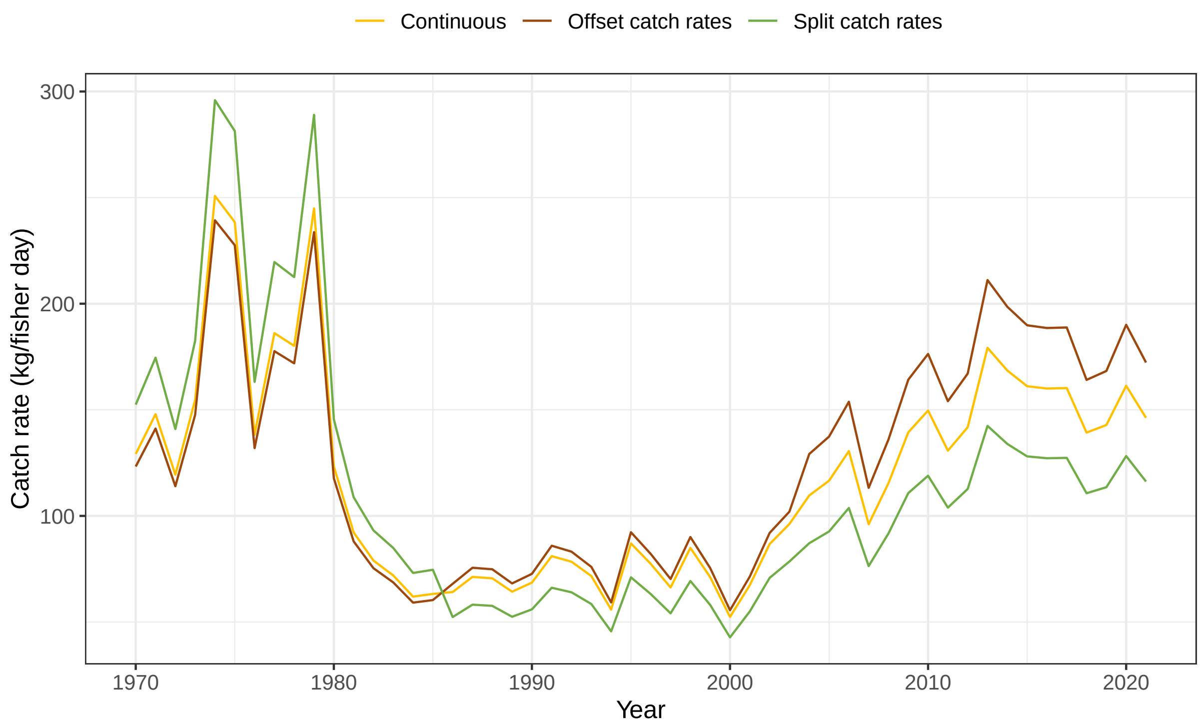


Figure A.1: Impact on catchability rescaling on how the population model perceives catch rates for tiger prawns

A.1.1 Catch rate standardisation diagnostics

Table A.1: Wald statistics for catch rate standardisation demonstrating the effect of dropping individual terms from full fixed model—denominator degrees of freedom for approximate F-tests are calculated using algebraic derivatives ignoring fixed/boundary/singular variance parameters

Fixed term	Wald statistic	n d.f.	F statistic	d d.f.	F pr
year.month	52825	506	104	1438229	0.00e+00
lunar	16027	1	16027	1441832	0.00e+00
lunar adv	89	1	89	1441808	4.88e-21
target	20202	1	20202	1441611	0.00e+00
loghours2	96902	1	96902	1442222	0.00e+00
logfracopen	20	1	20	1139255	7.43e-06

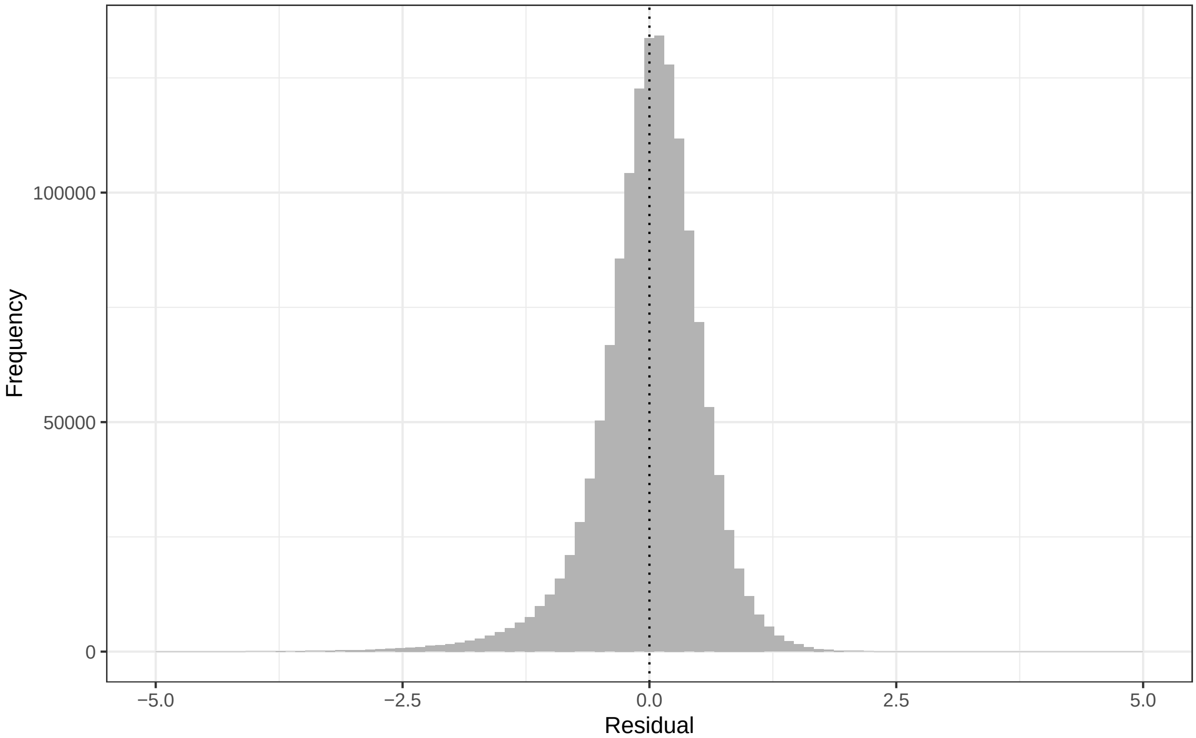


Figure A.2: Standardised catch rates residuals

Table A.2: Targeting analysis on how associated species are caught with tiger prawns

Associated species	Tiger prawn correlation	Tiger prawn ratio	Tiger prawn diff
Tiger	1	1.79	63.61
Banana	-0.03	0.98	-1.44
Endeavour	0.17	1.09	7.67
Redspot	-0.23	0.88	-7.02
Mudbug	-0.13	0.96	-3.45
Sandbug	-0.22	0.81	-12.57
Scallop	-0.18	0.88	-9.6
EKP	0	0	0

A.1.2 Fishing power

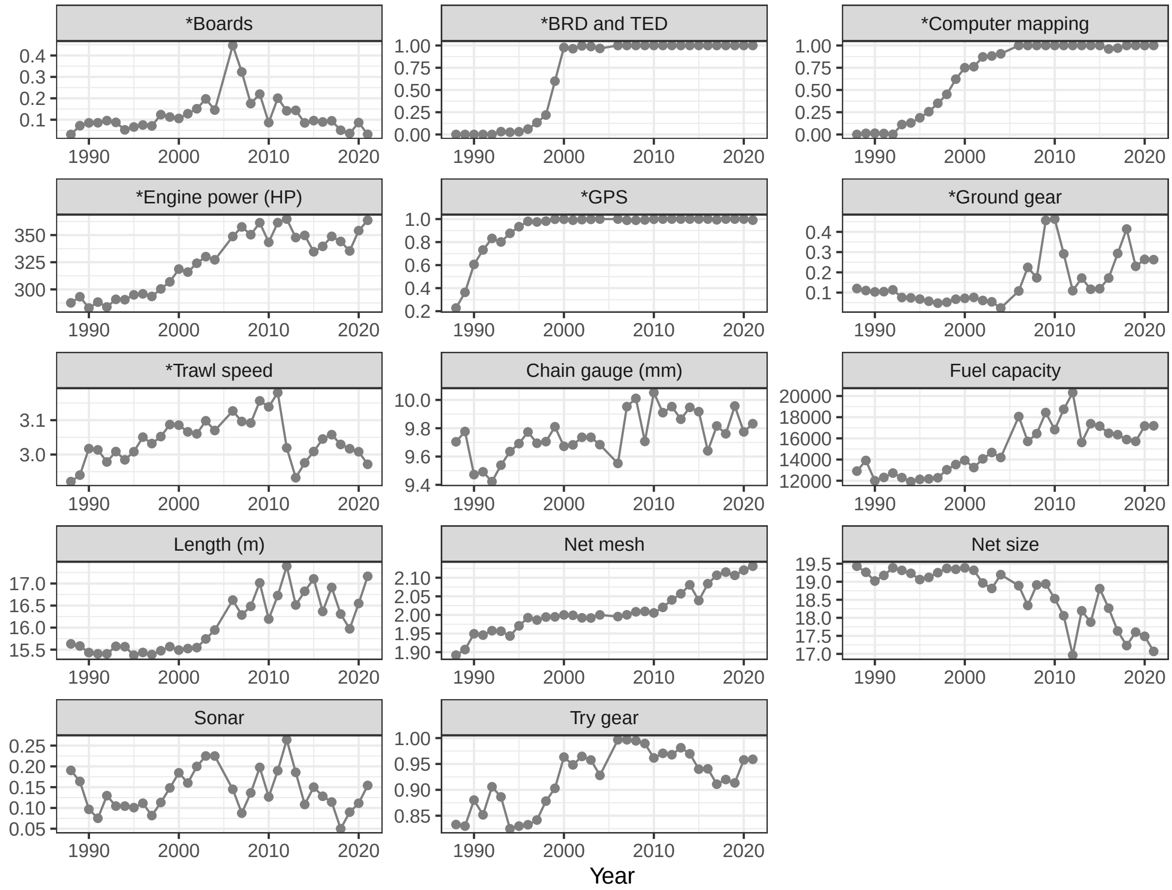


Figure A.3: Fishing power gear trends—asterisks represent variables that were eventually included in the fishing power model

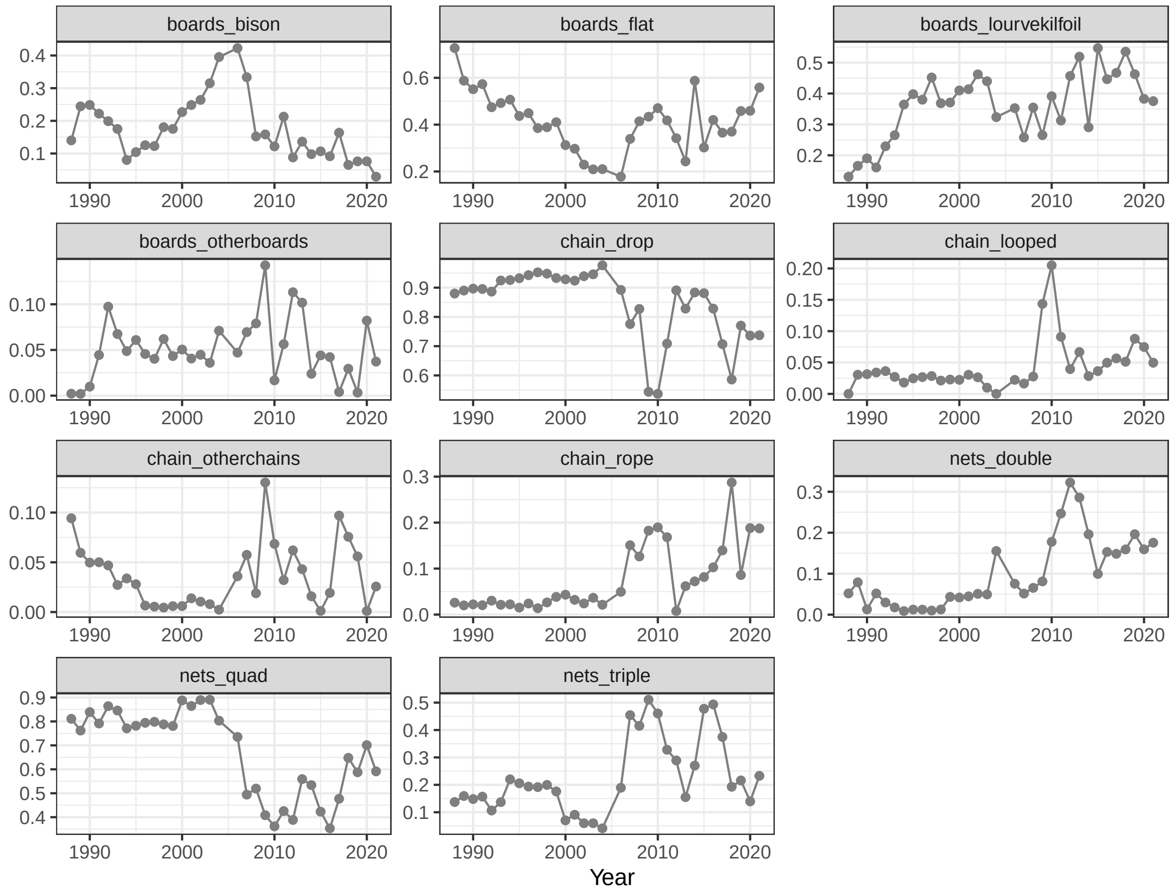


Figure A.4: Fishing power gear trends continued

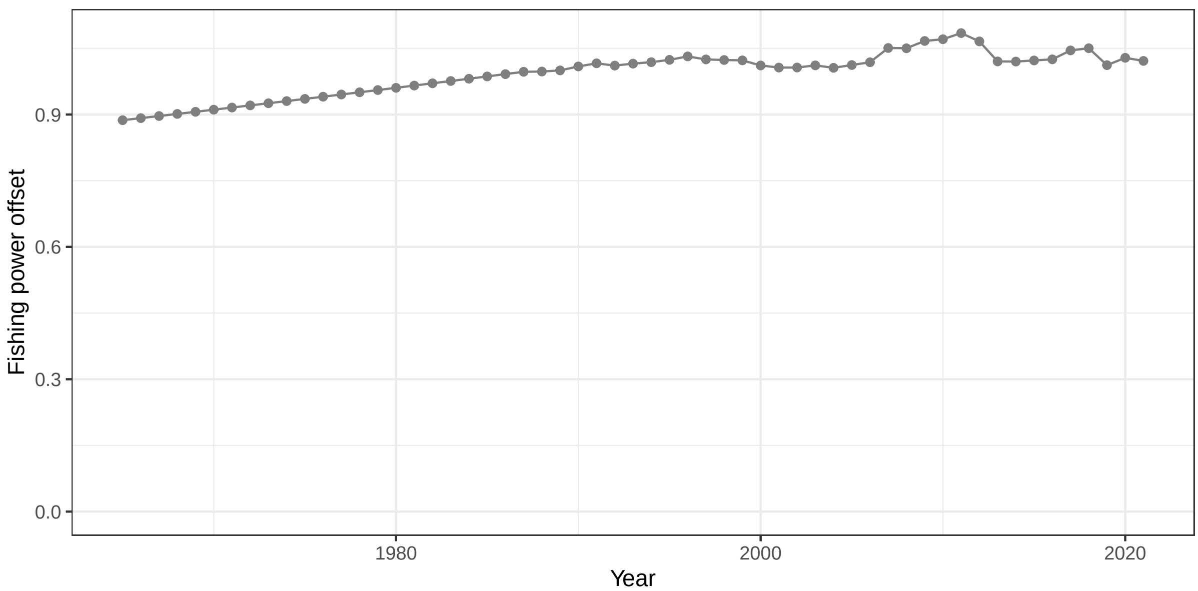


Figure A.5: Fishing power offset used as a variable in the catch rate standardisation model

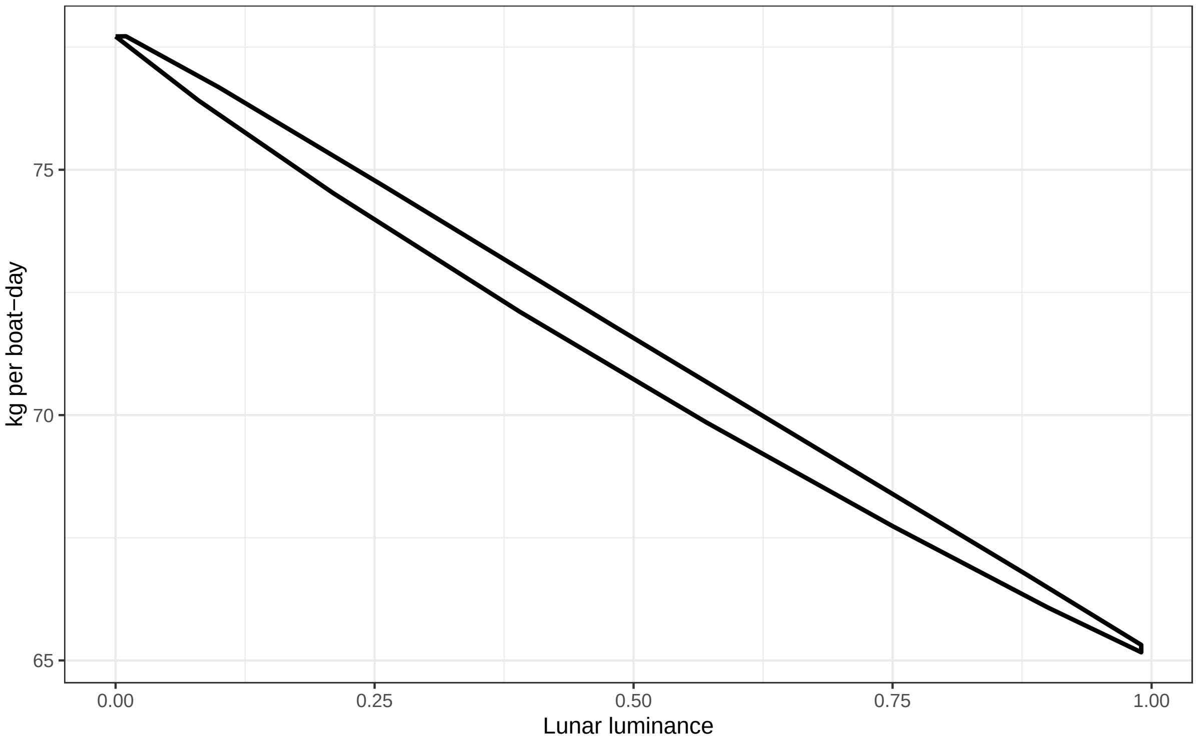


Figure A.6: Influence of lunar luminance on catch rates

A.2 Biological data

A.2.1 Weight and age

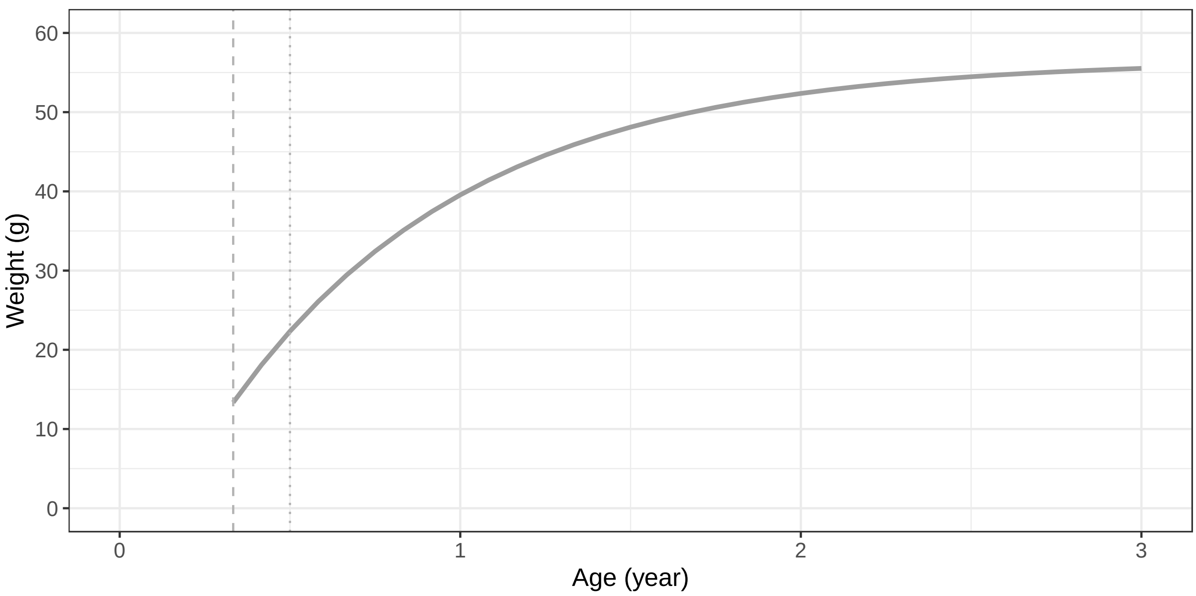


Figure A.7: Weight at age—dashed line represents age at recruitment (4 months) and dotted line represents age at maturity (6 months)

A.2.2 Fecundity and maturity

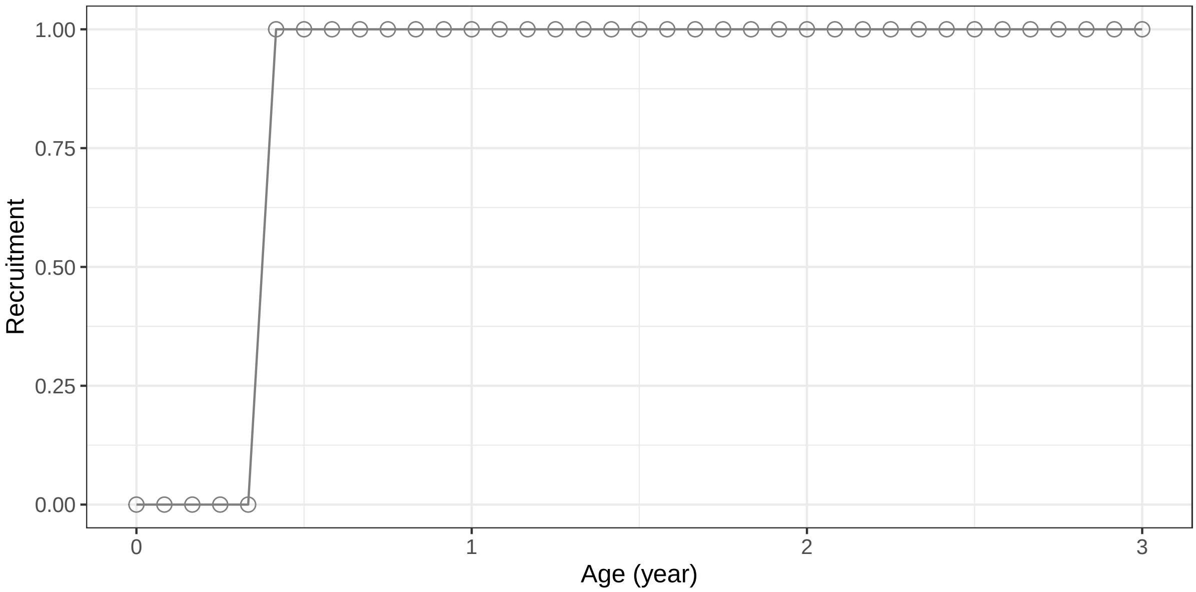


Figure A.8: Recruitment to the fishery at age

Appendix B Model outputs

B.1 MCMC diagnostics

B.1.1 Potential scale reduction factor

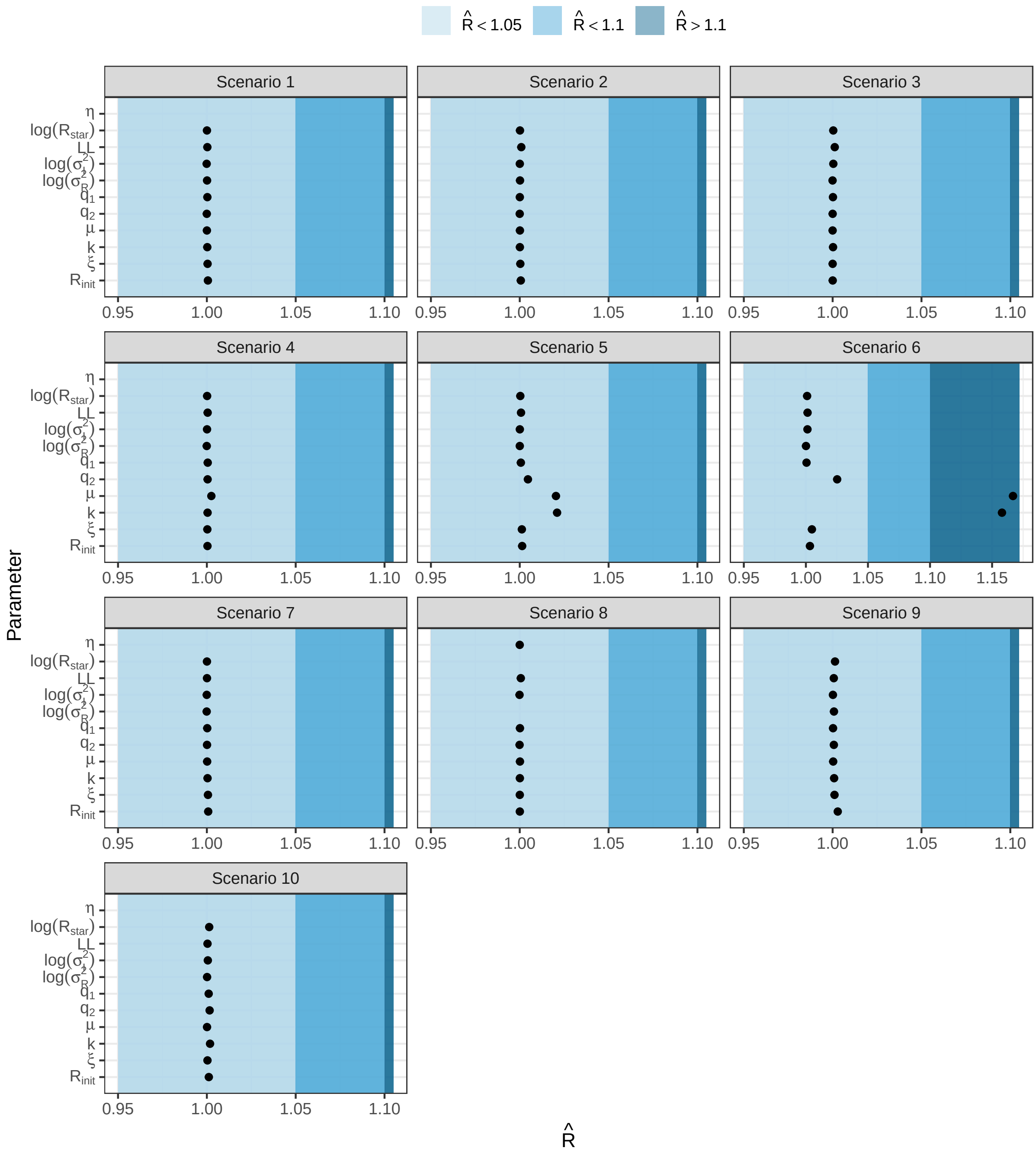


Figure B.1: Potential scale reduction factor, $\hat{R}$ values among the scenarios for east coast tiger prawns—model is likely converged if $\hat{R} < 1.05$

B.1.2 Posterior density plots

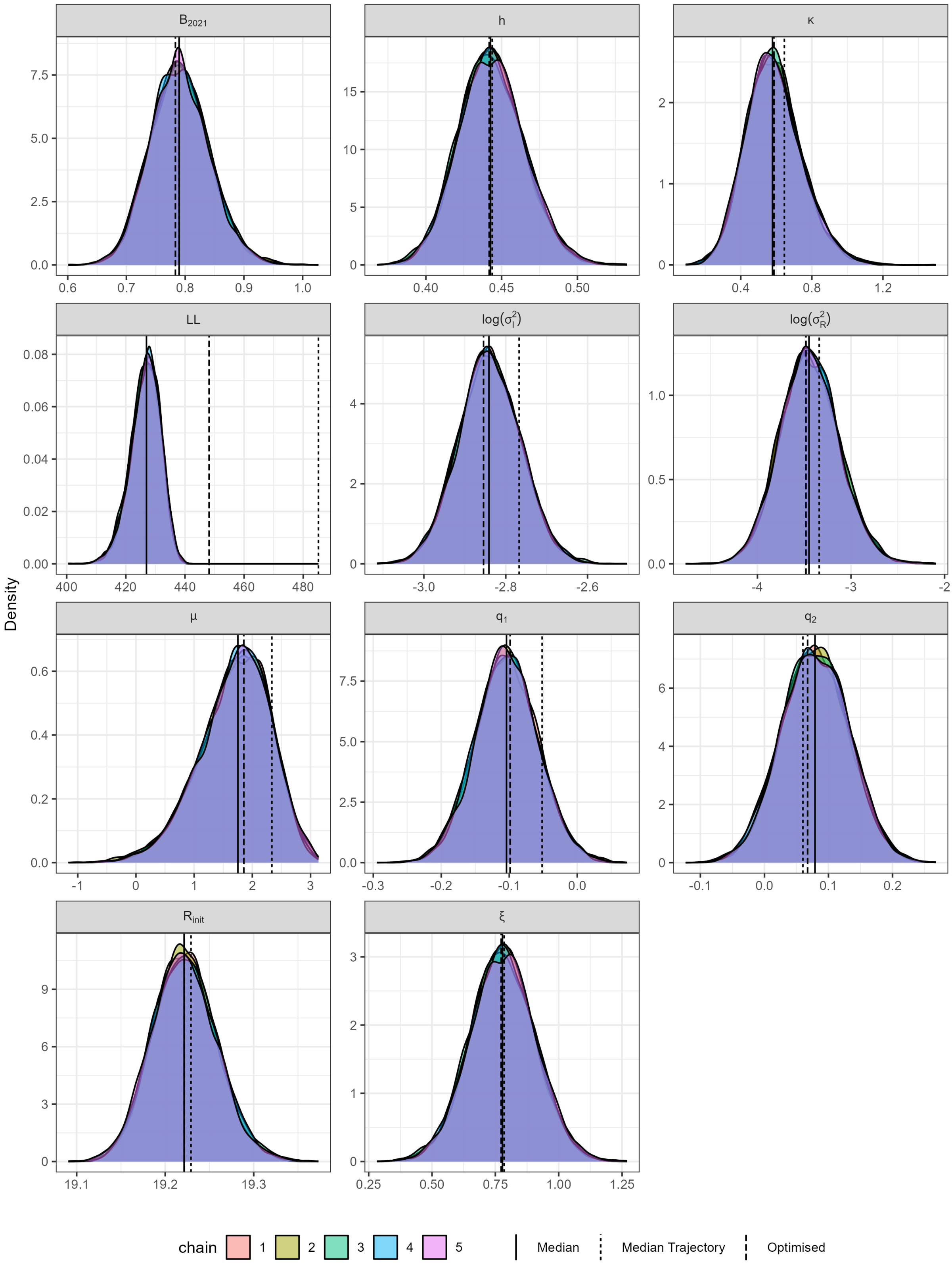


Figure B.2: Posterior density of MCMC chains for tiger prawns scenario 1. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

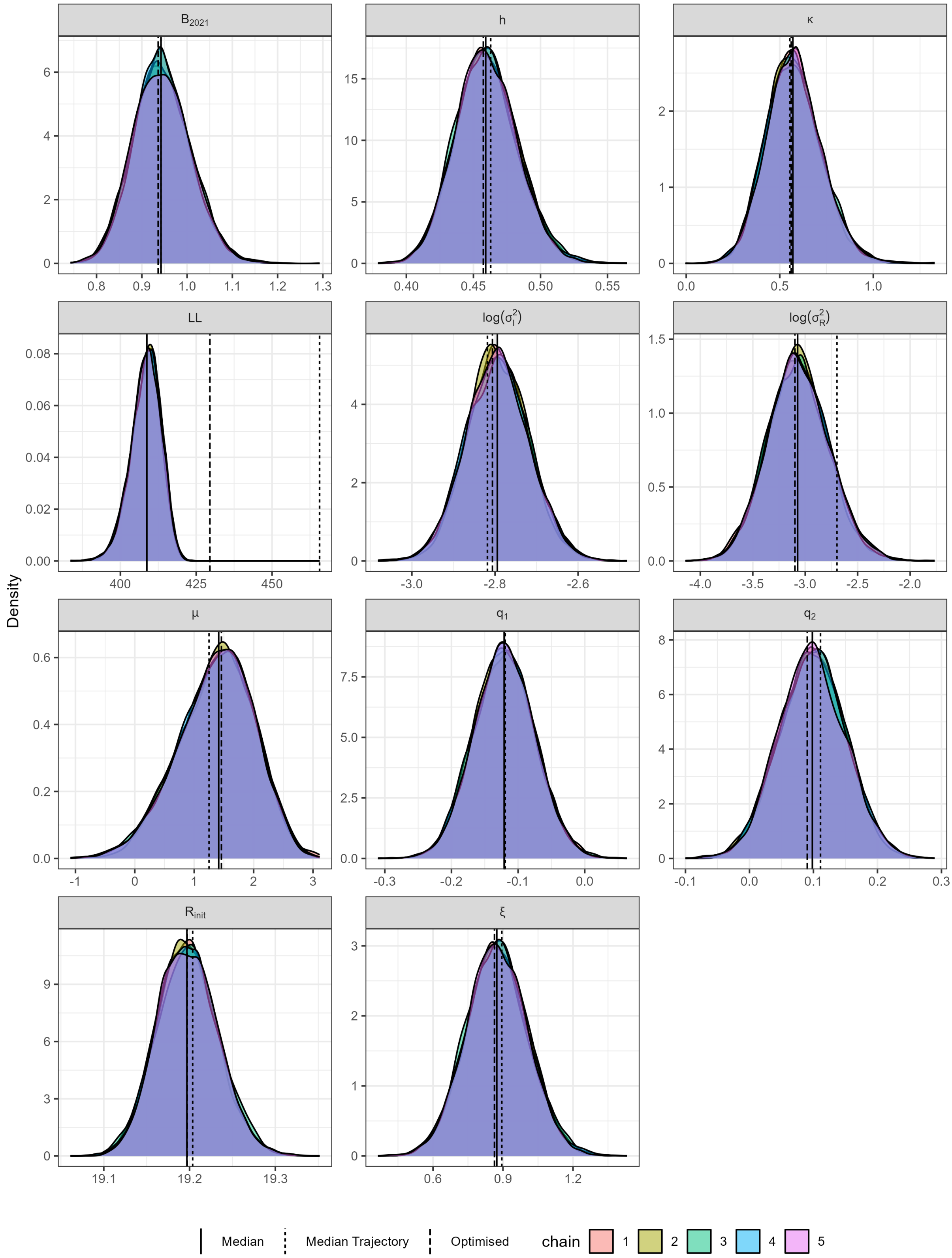


Figure B.3: Posterior density of MCMC chains for tiger prawns scenario 2. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

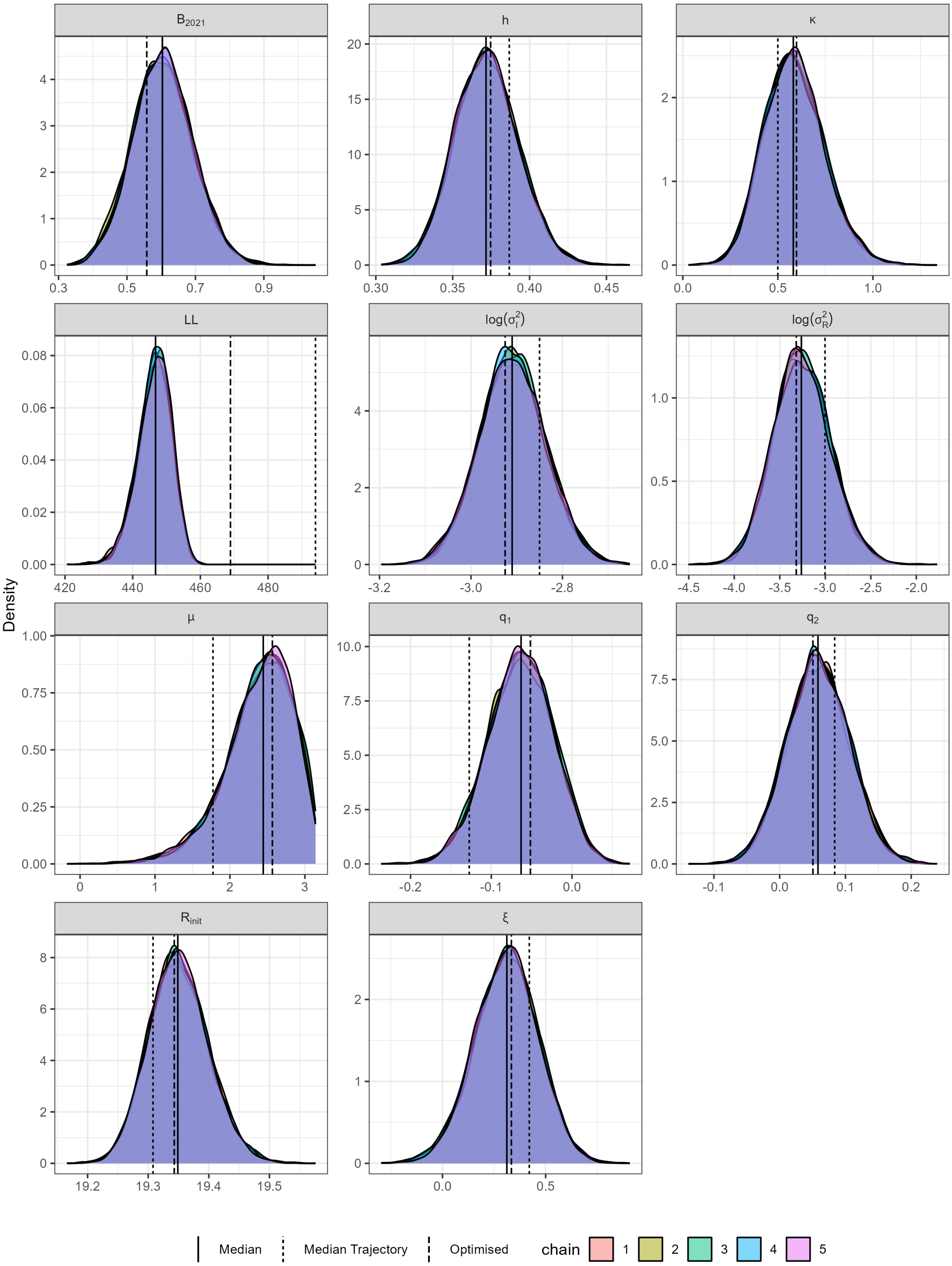


Figure B.4: Posterior density of MCMC chains for tiger prawns scenario 3. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

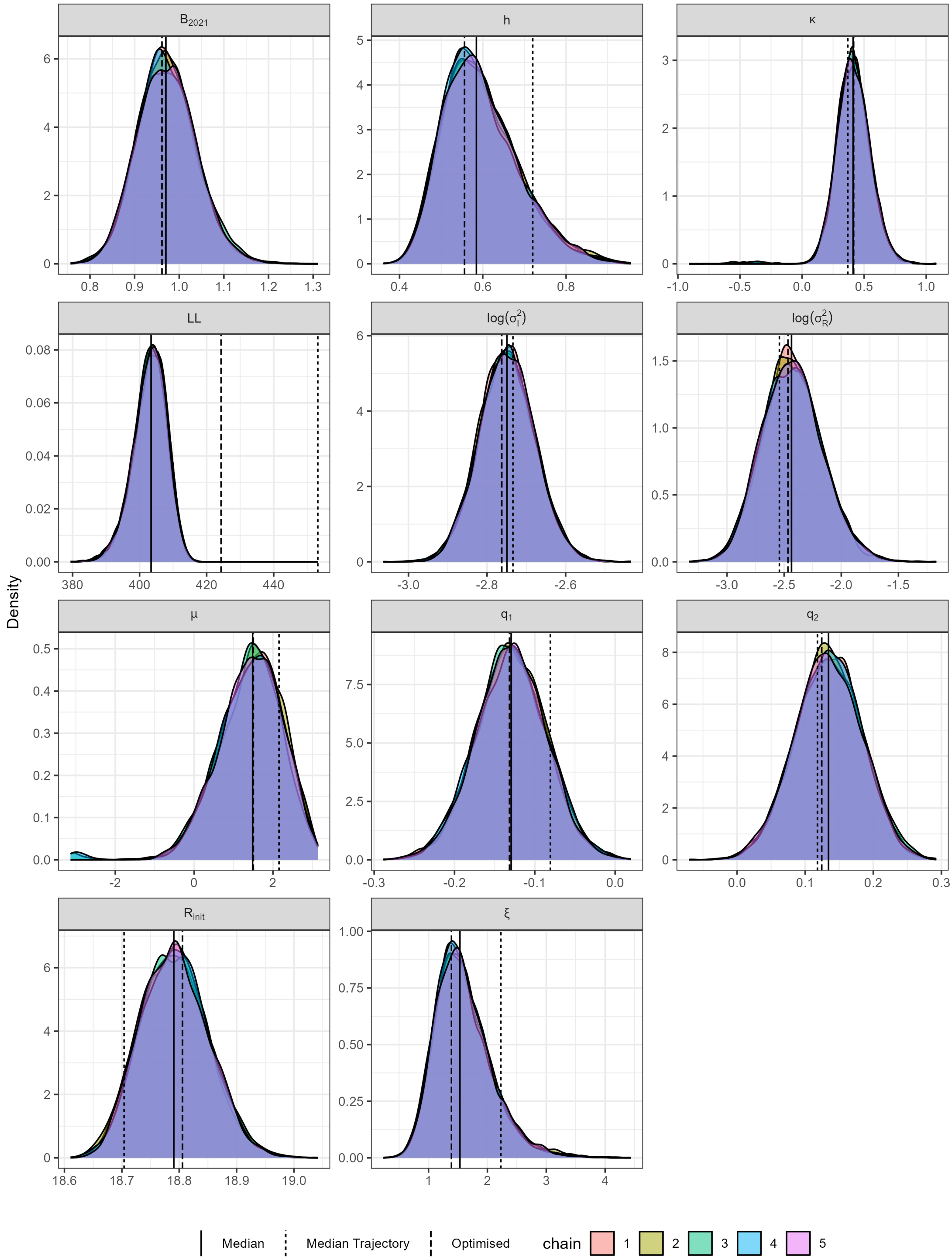


Figure B.5: Posterior density of MCMC chains for tiger prawns scenario 4. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

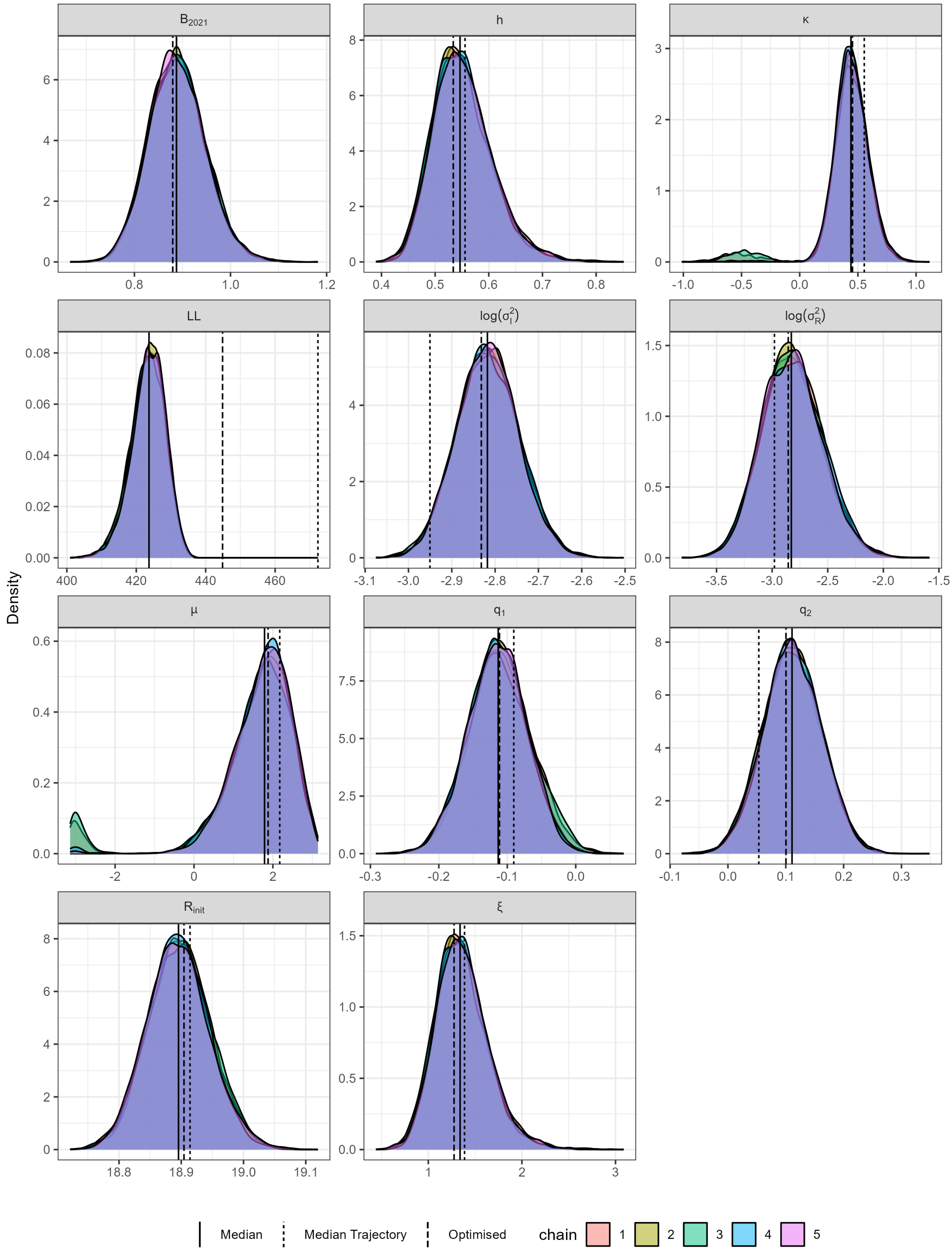


Figure B.6: Posterior density of MCMC chains for tiger prawns scenario 5. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

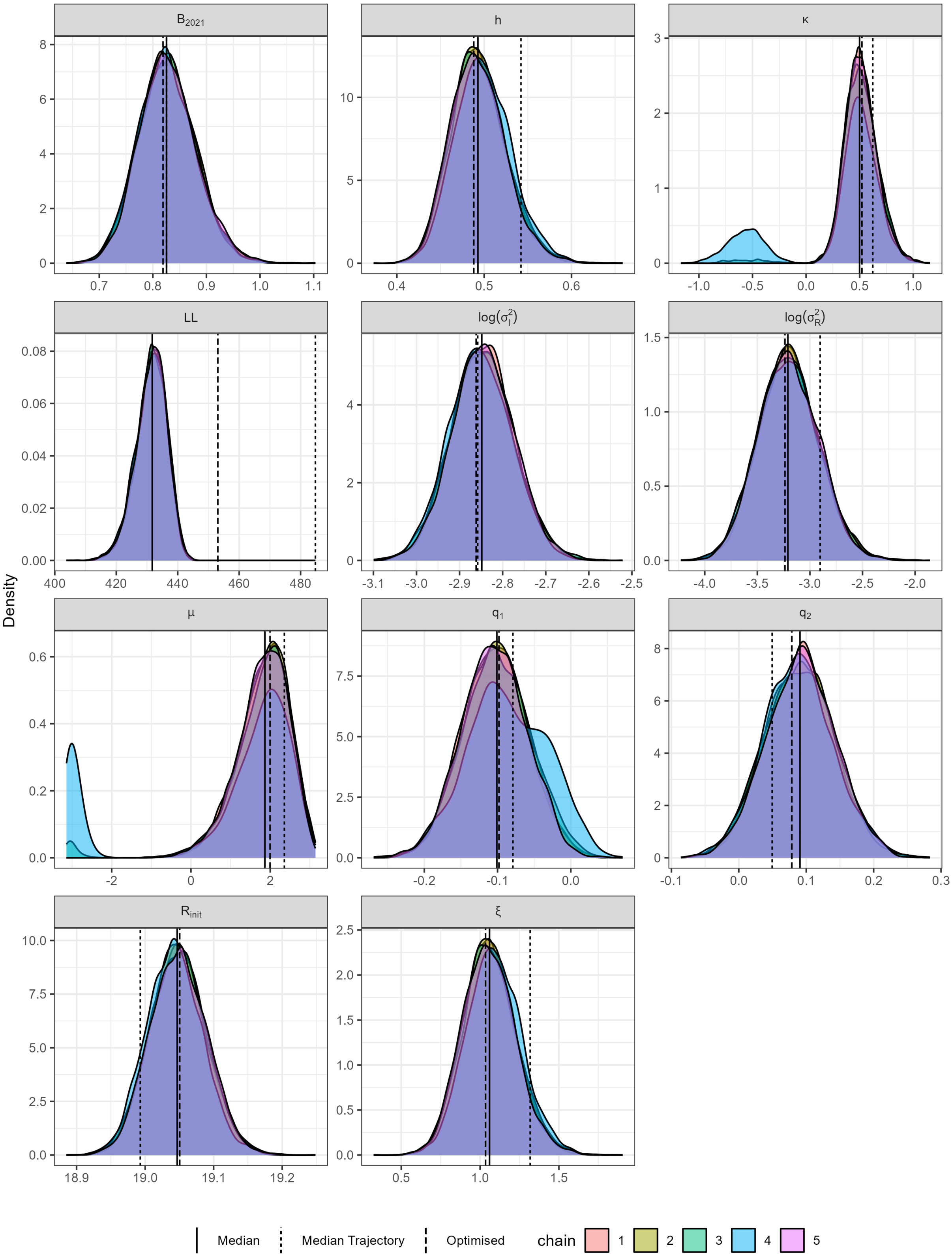


Figure B.7: Posterior density of MCMC chains for tiger prawns scenario 6. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

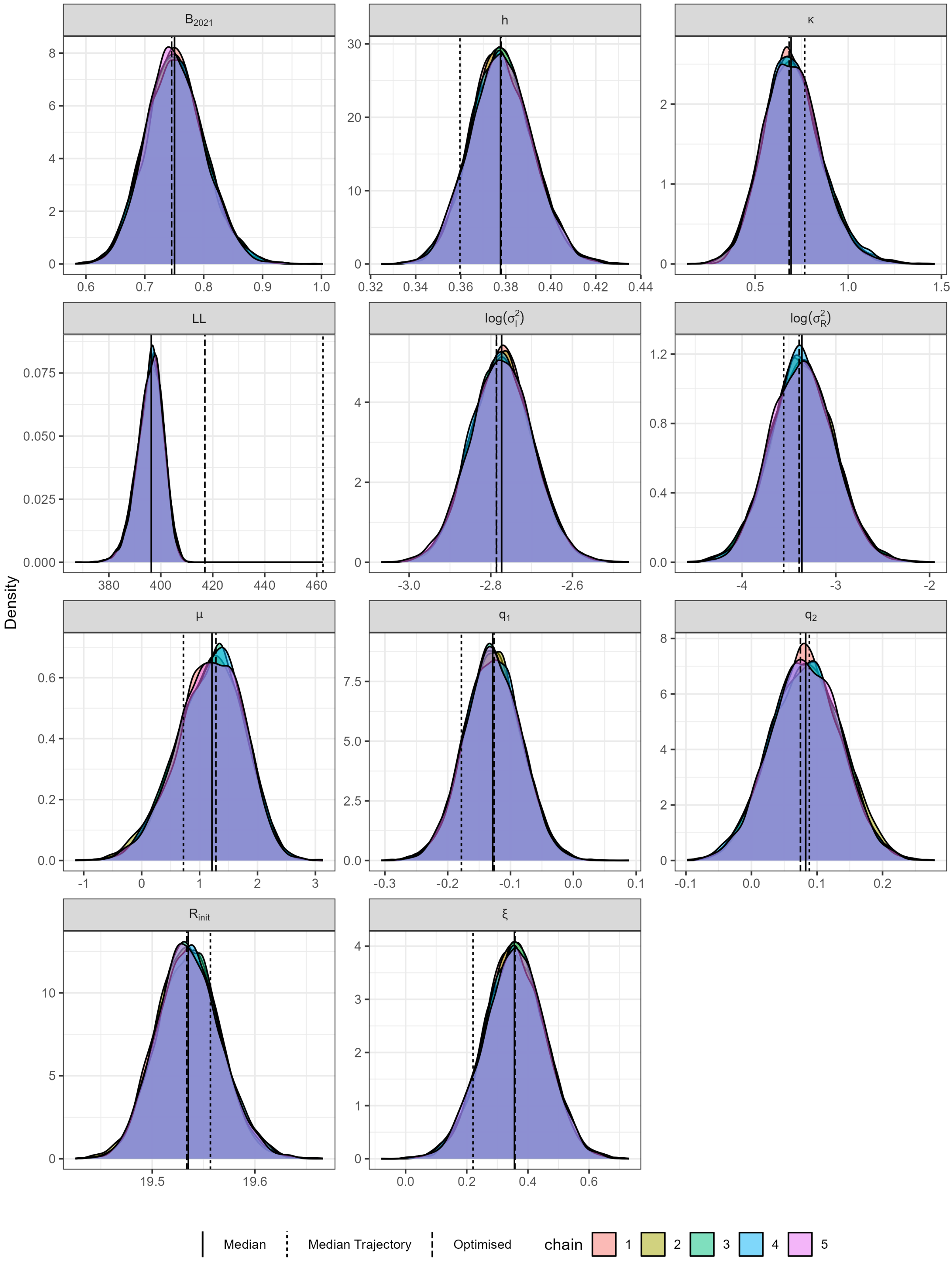


Figure B.8: Posterior density of MCMC chains for tiger prawns scenario 7. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

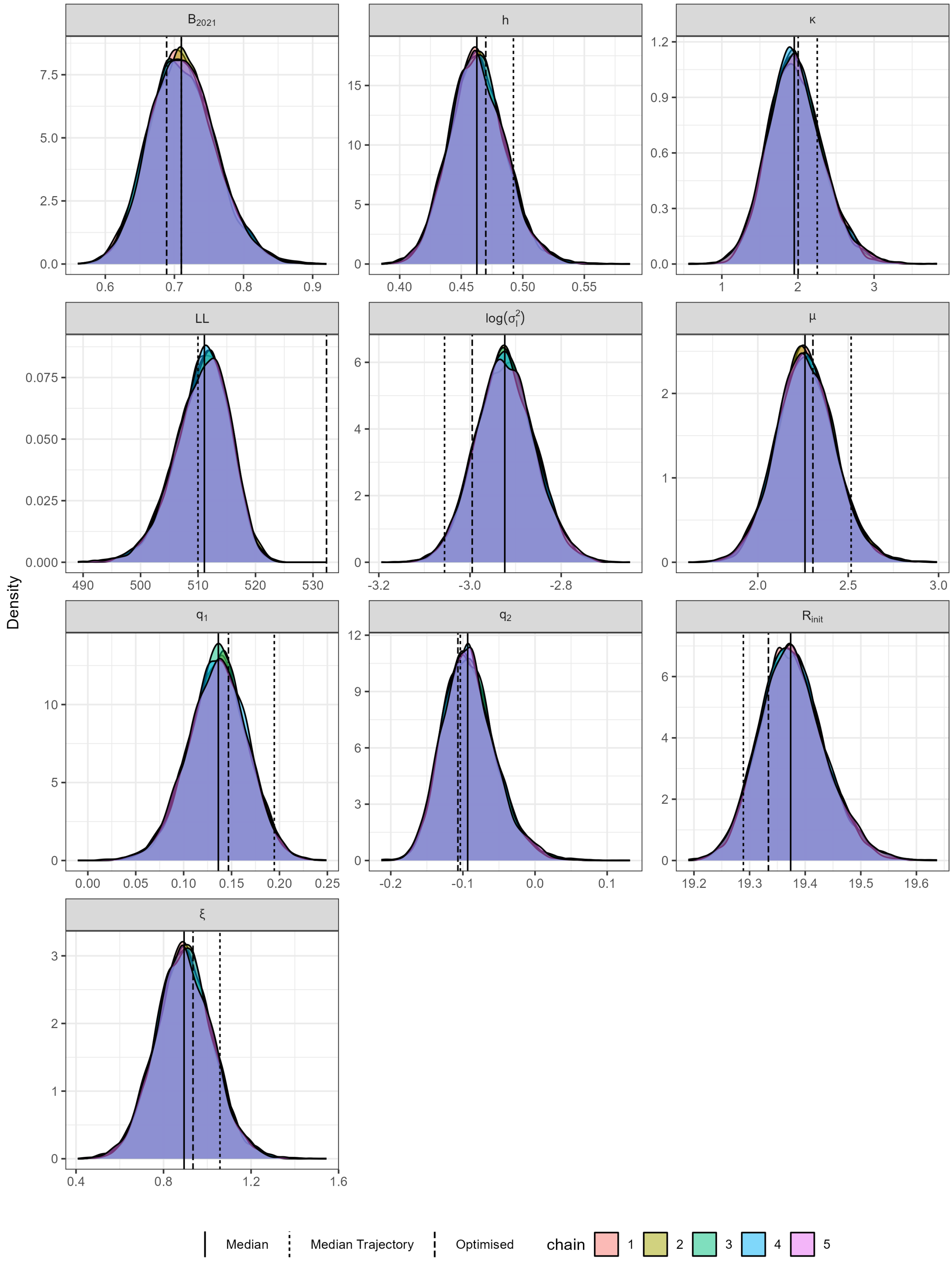


Figure B.9: Posterior density of MCMC chains for tiger prawns scenario 8. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

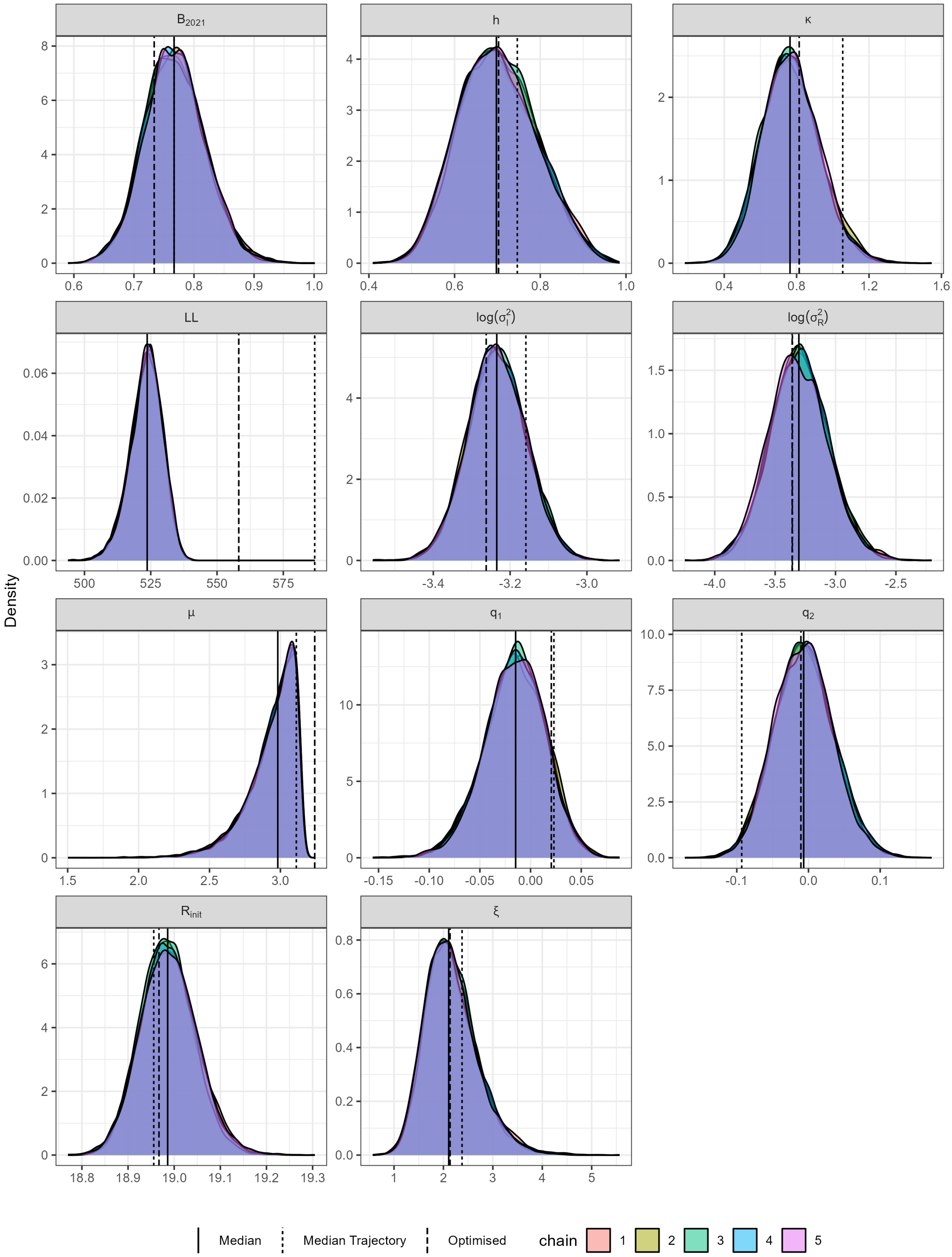


Figure B.10: Posterior density of MCMC chains for tiger prawns scenario 9. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

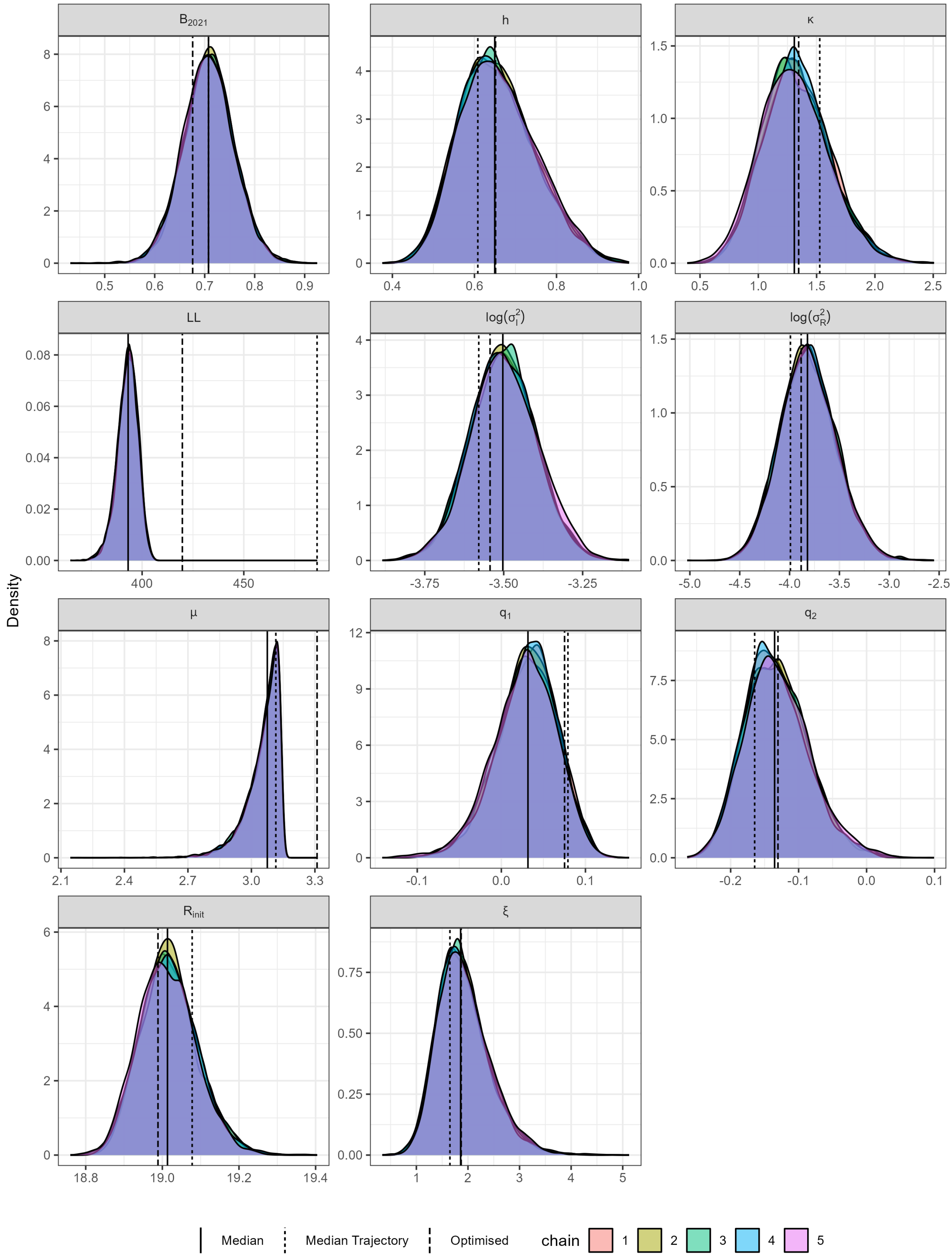


Figure B.11: Posterior density of MCMC chains for tiger prawns scenario 10. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

B.1.3 Trace plots

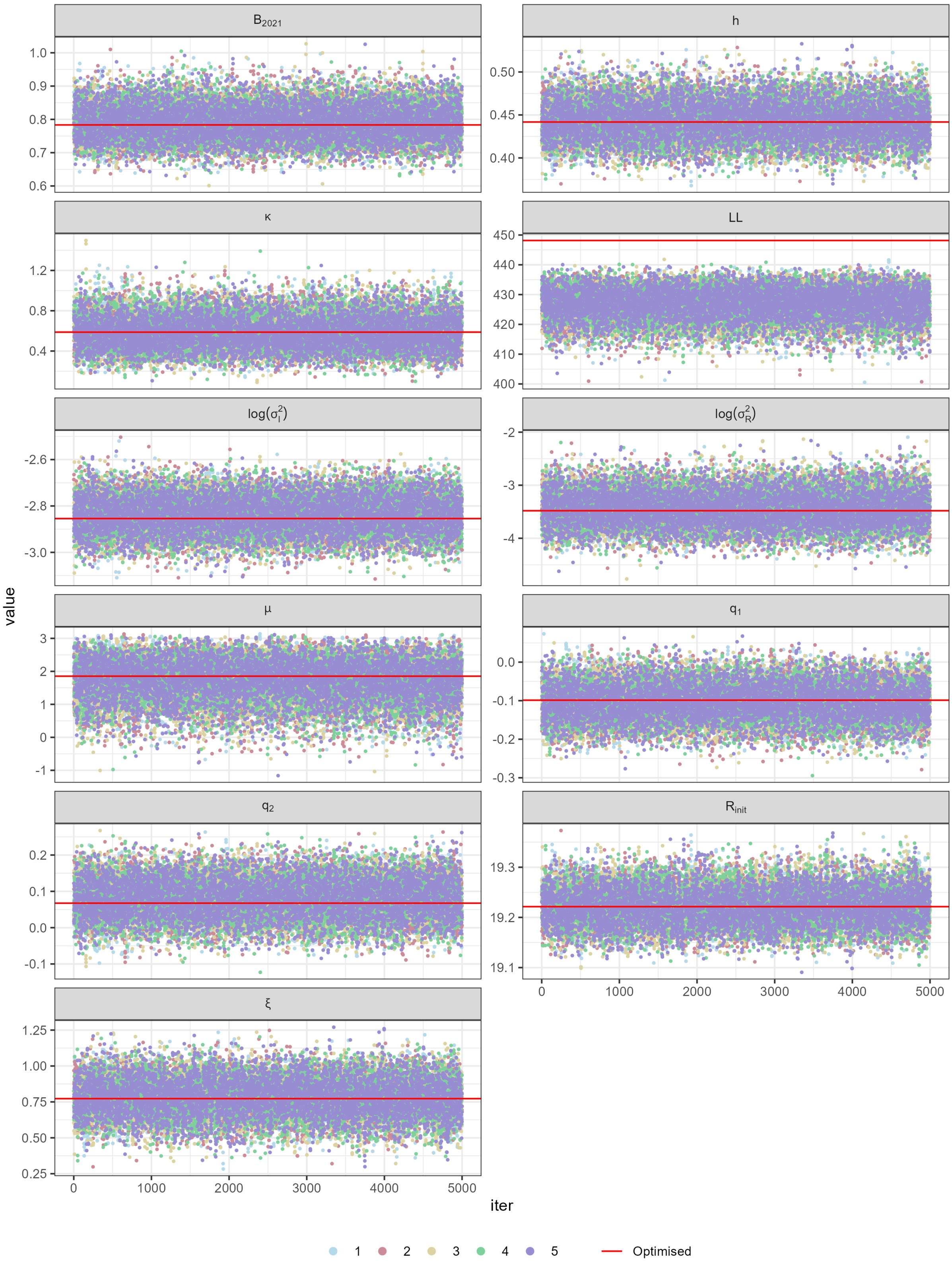


Figure B.12: Trace plot of MCMC chains for tiger prawns scenario 1—'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

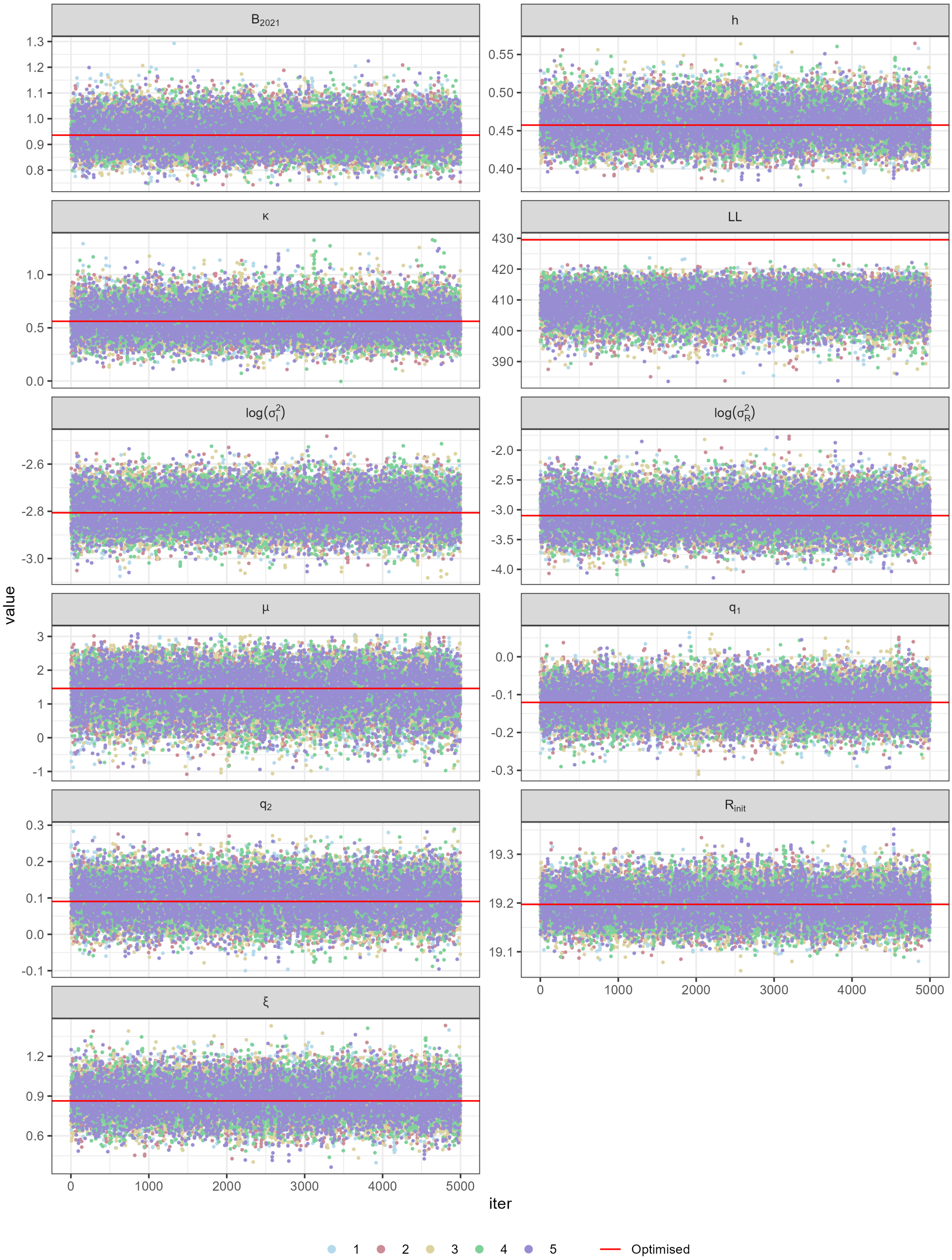


Figure B.13: Trace plot of MCMC chains for tiger prawns scenario 2—'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

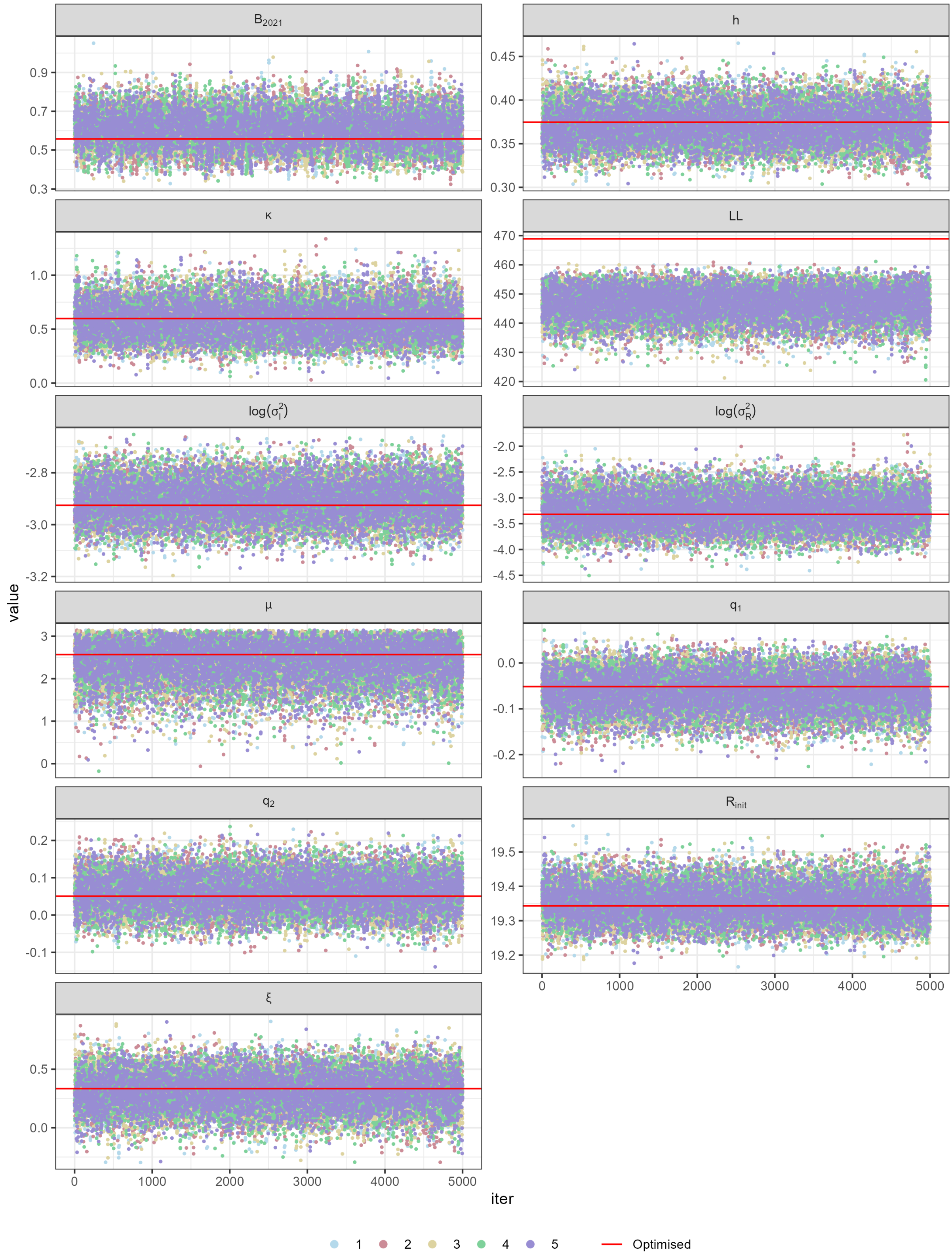


Figure B.14: Trace plot of MCMC chains for tiger prawns scenario 3—'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

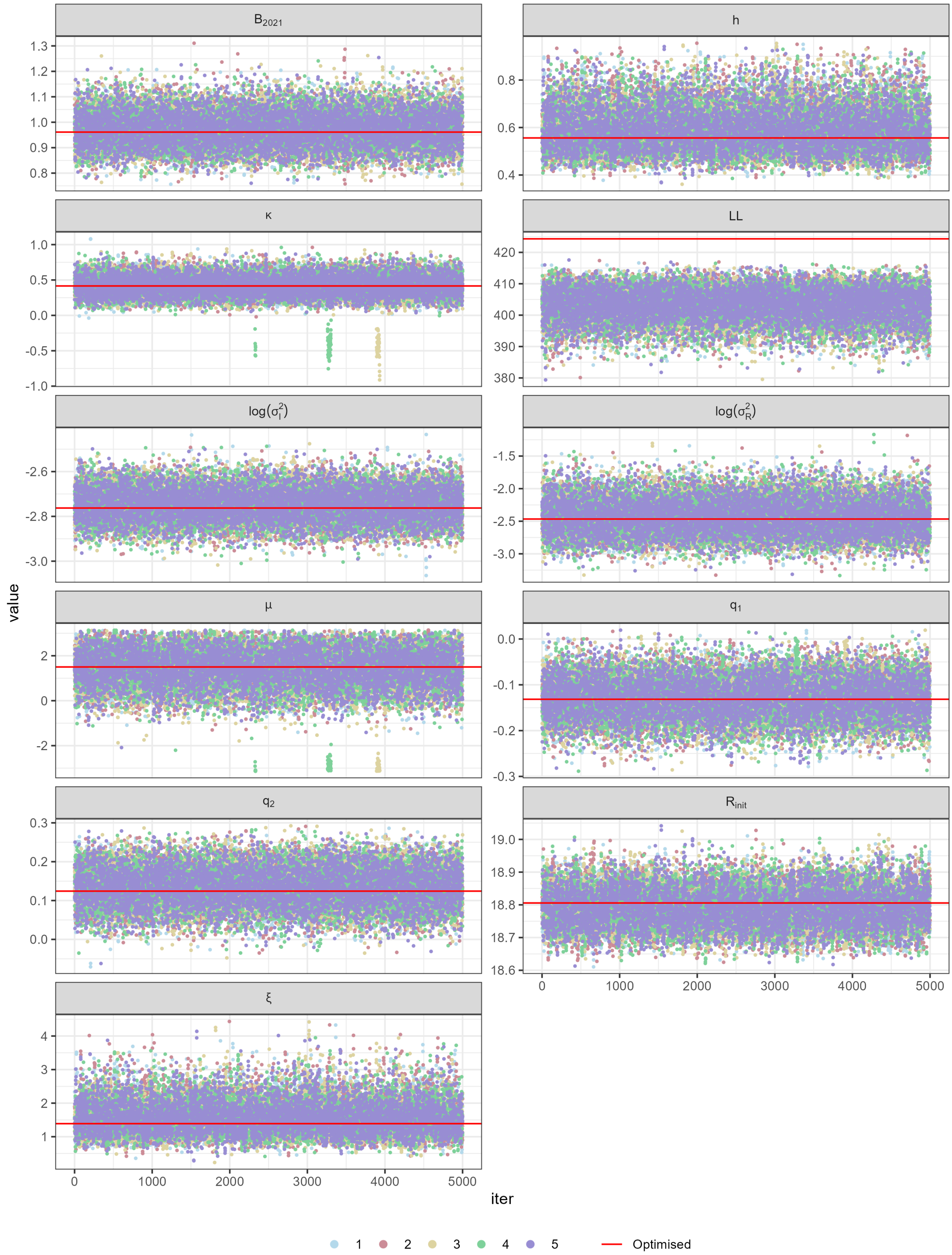


Figure B.15: Trace plot of MCMC chains for tiger prawns scenario 4—'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

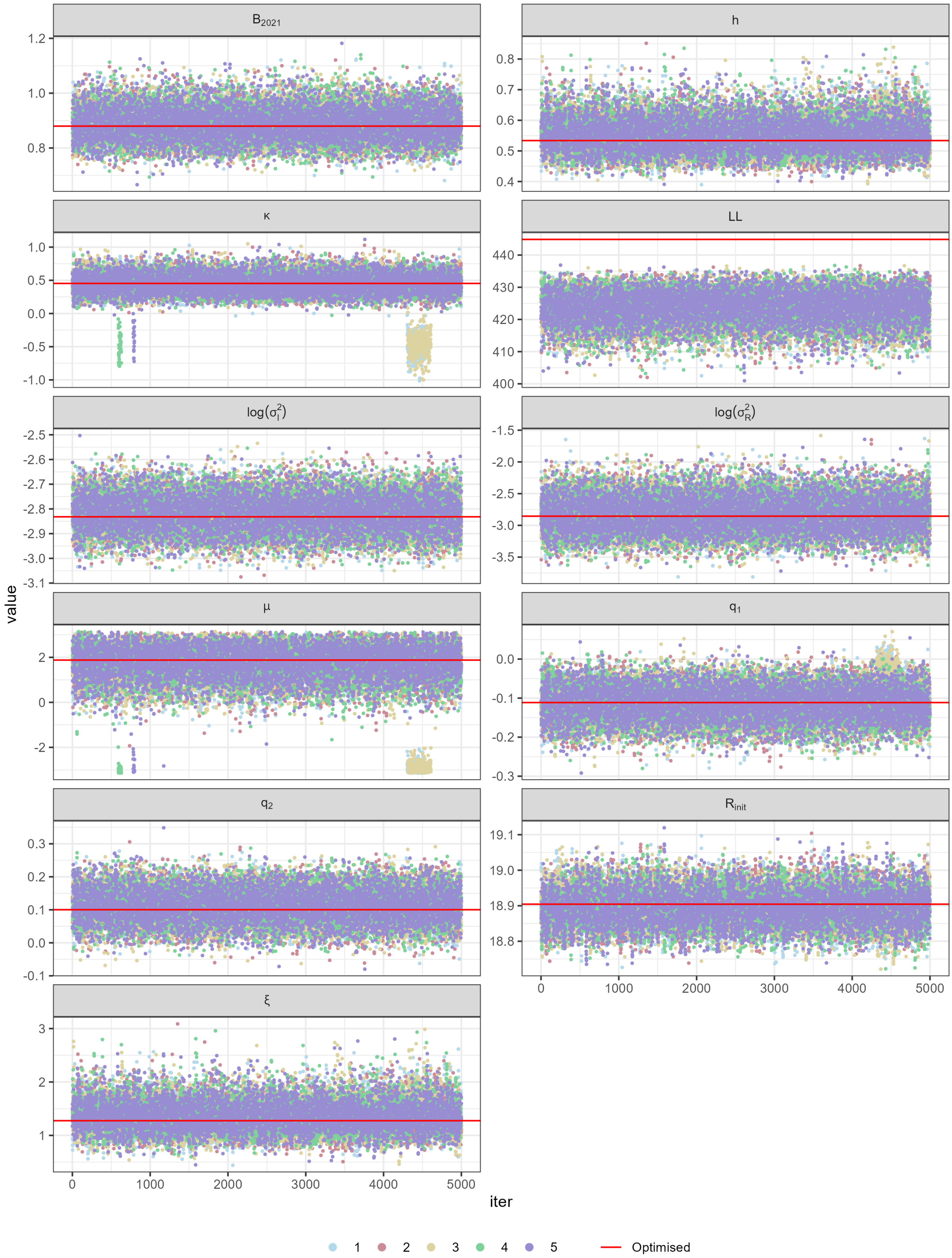


Figure B.16: Trace plot of MCMC chains for tiger prawns scenario 5—'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

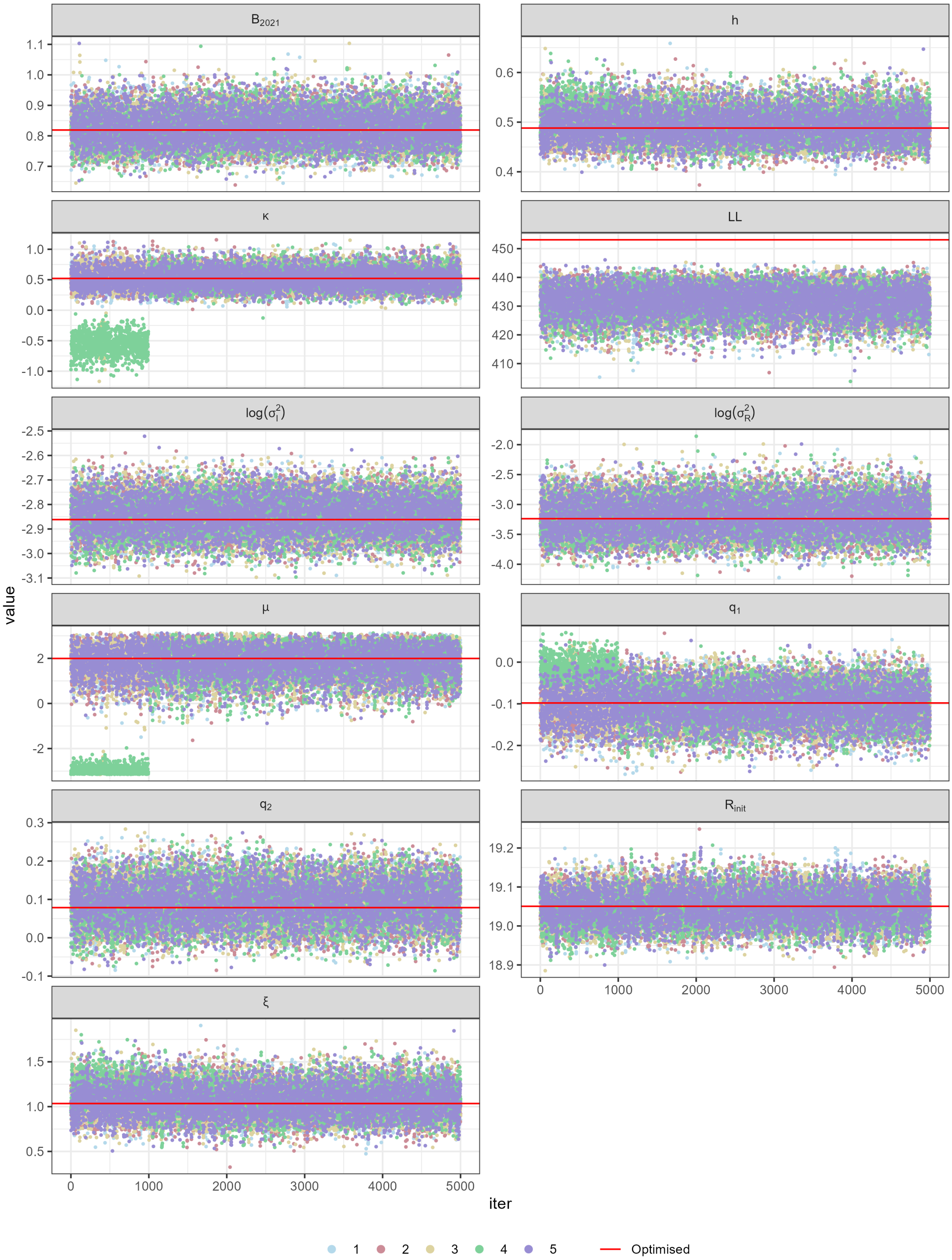


Figure B.17: Trace plot of MCMC chains for tiger prawns scenario 6—'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

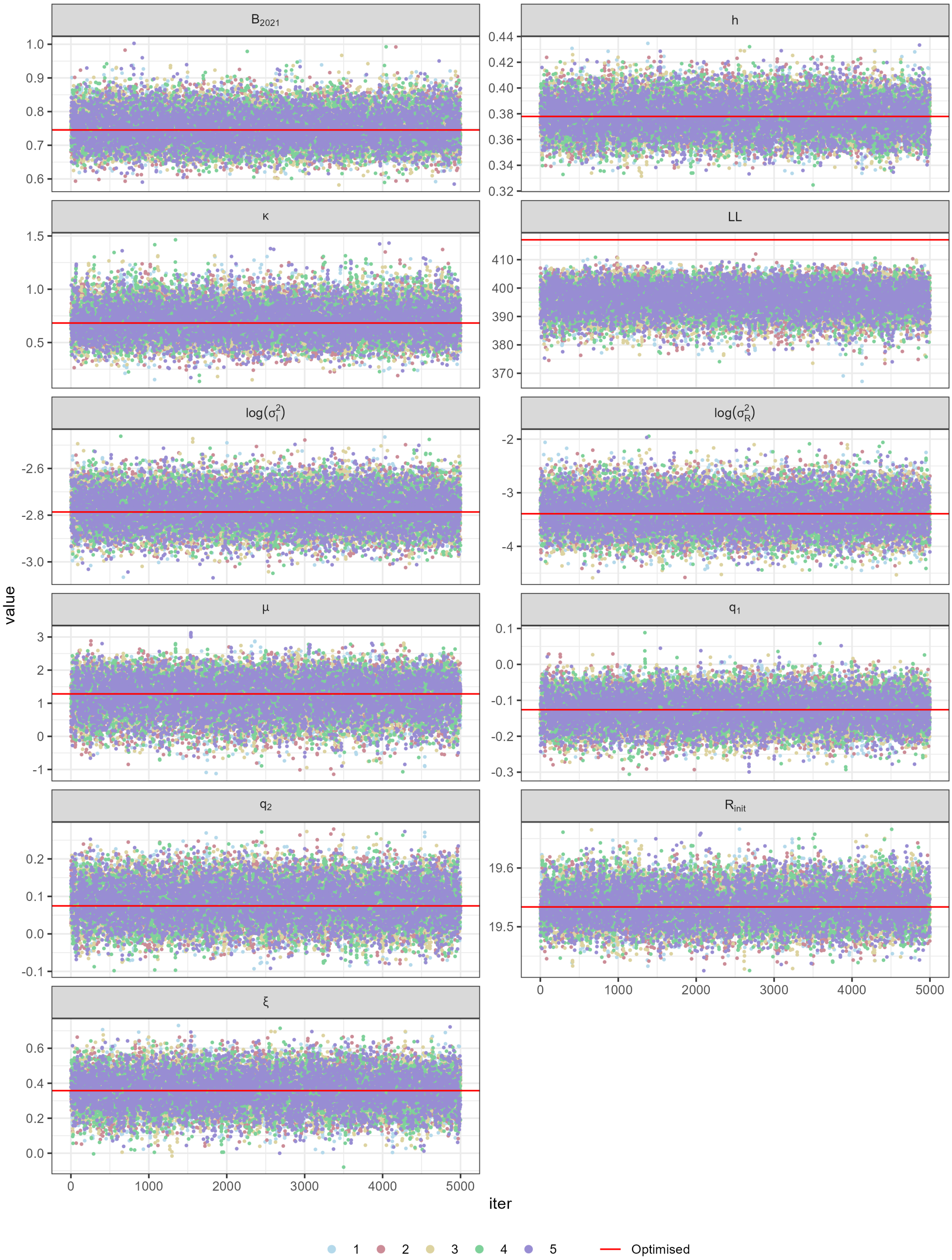


Figure B.18: Trace plot of MCMC chains for tiger prawns scenario 7—'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

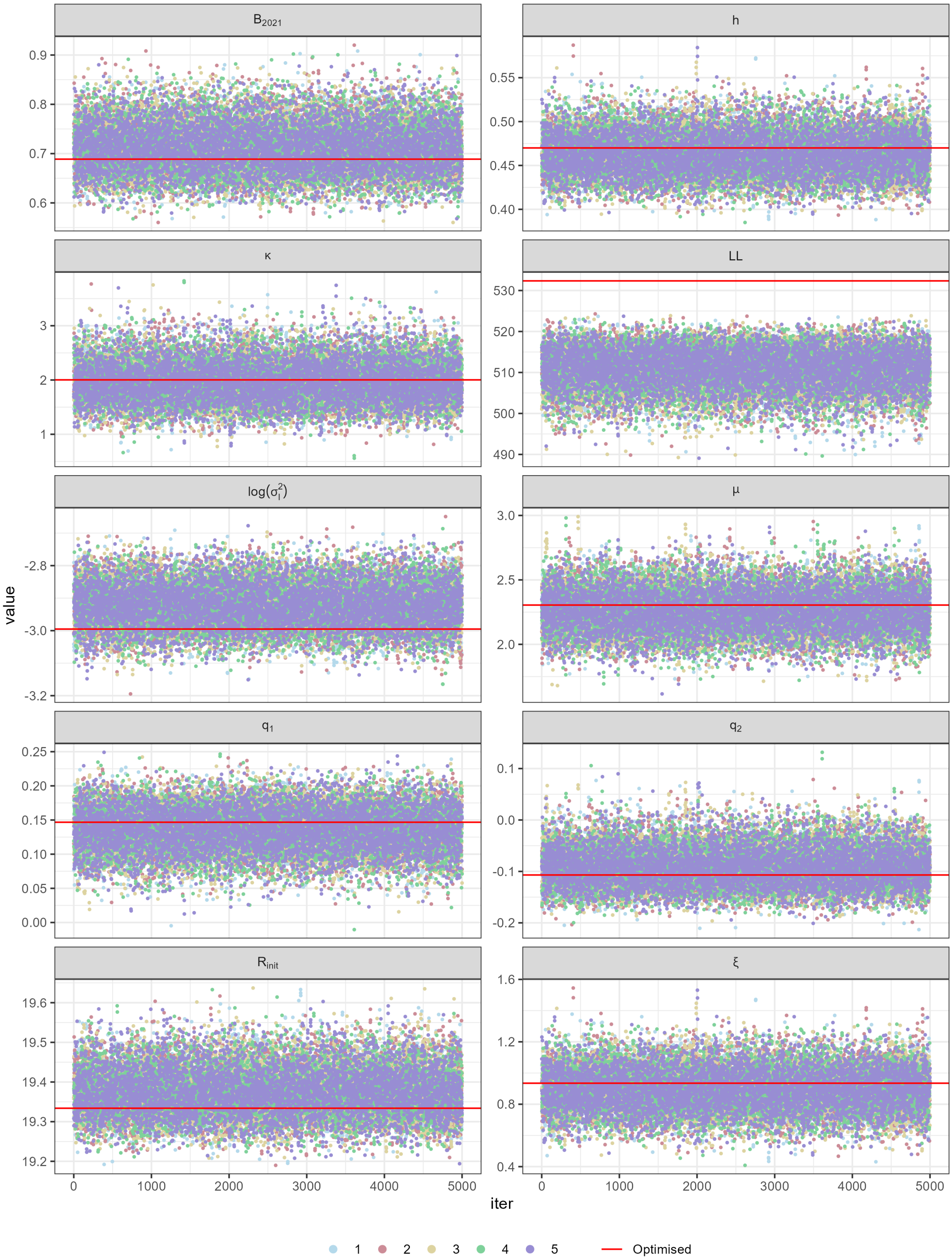


Figure B.19: Trace plot of MCMC chains for tiger prawns scenario 8—'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

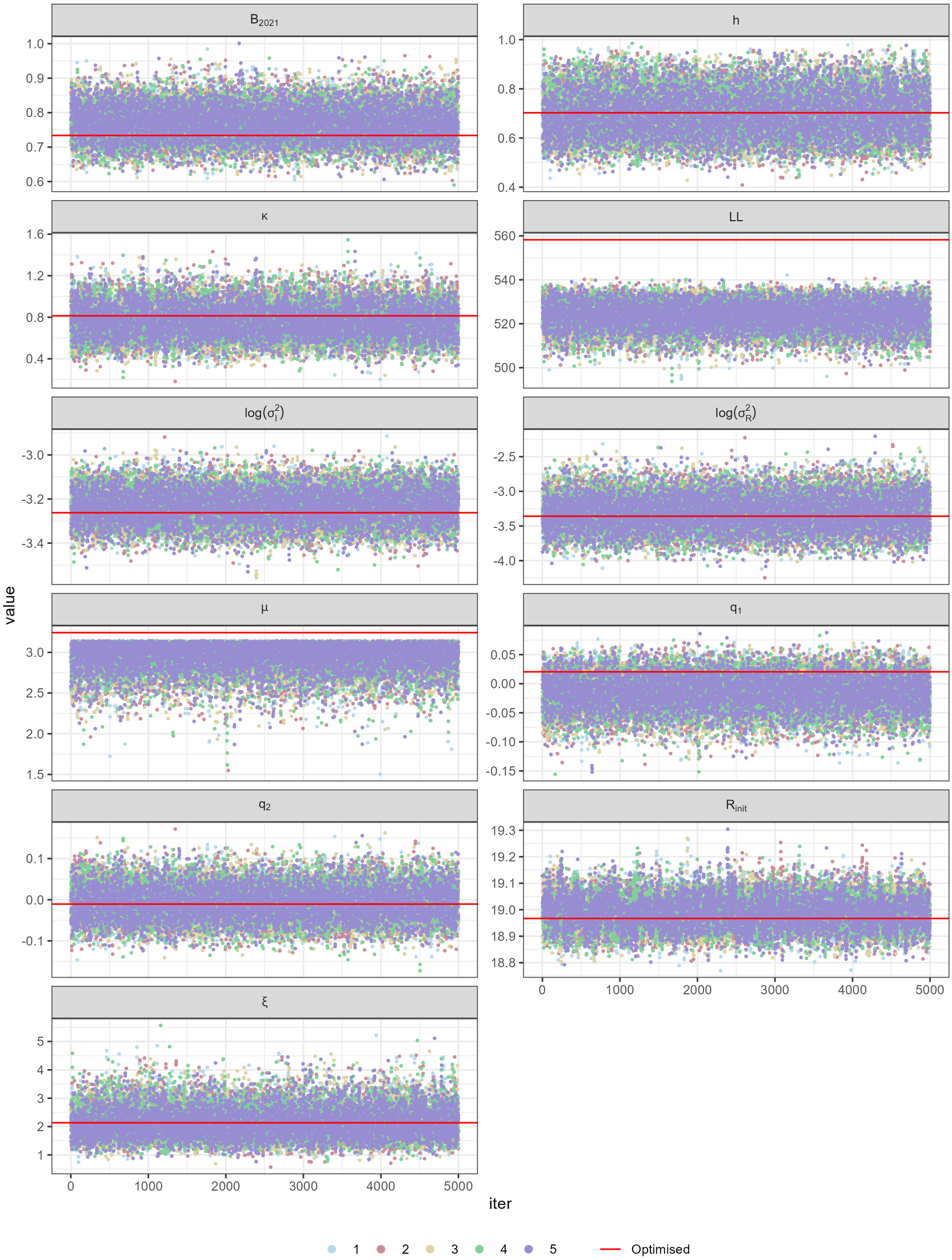


Figure B.20: Trace plot of MCMC chains for tiger prawns scenario 9—'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

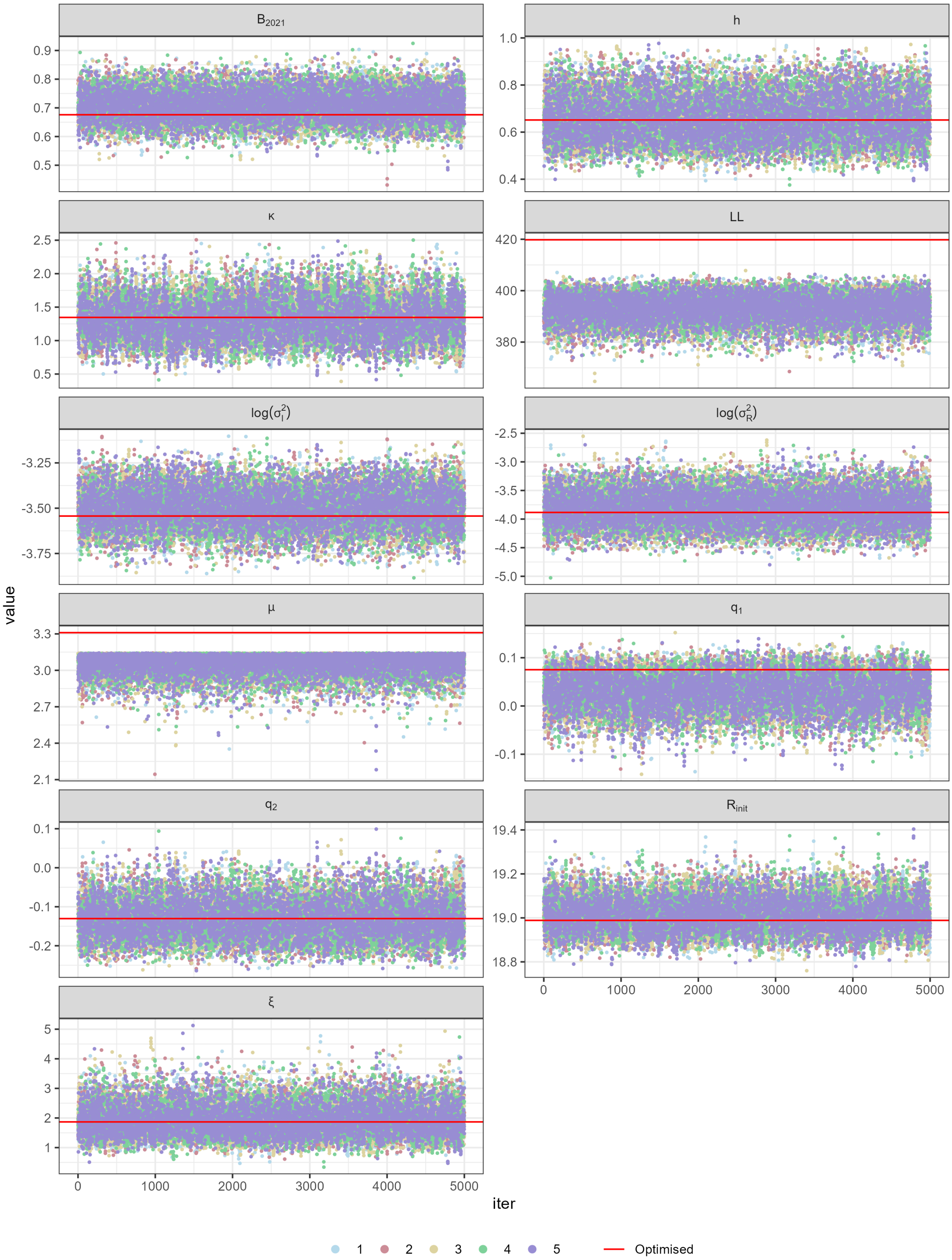


Figure B.21: Trace plot of MCMC chains for tiger prawns scenario 10—'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function

B.1.4 Correlation plots

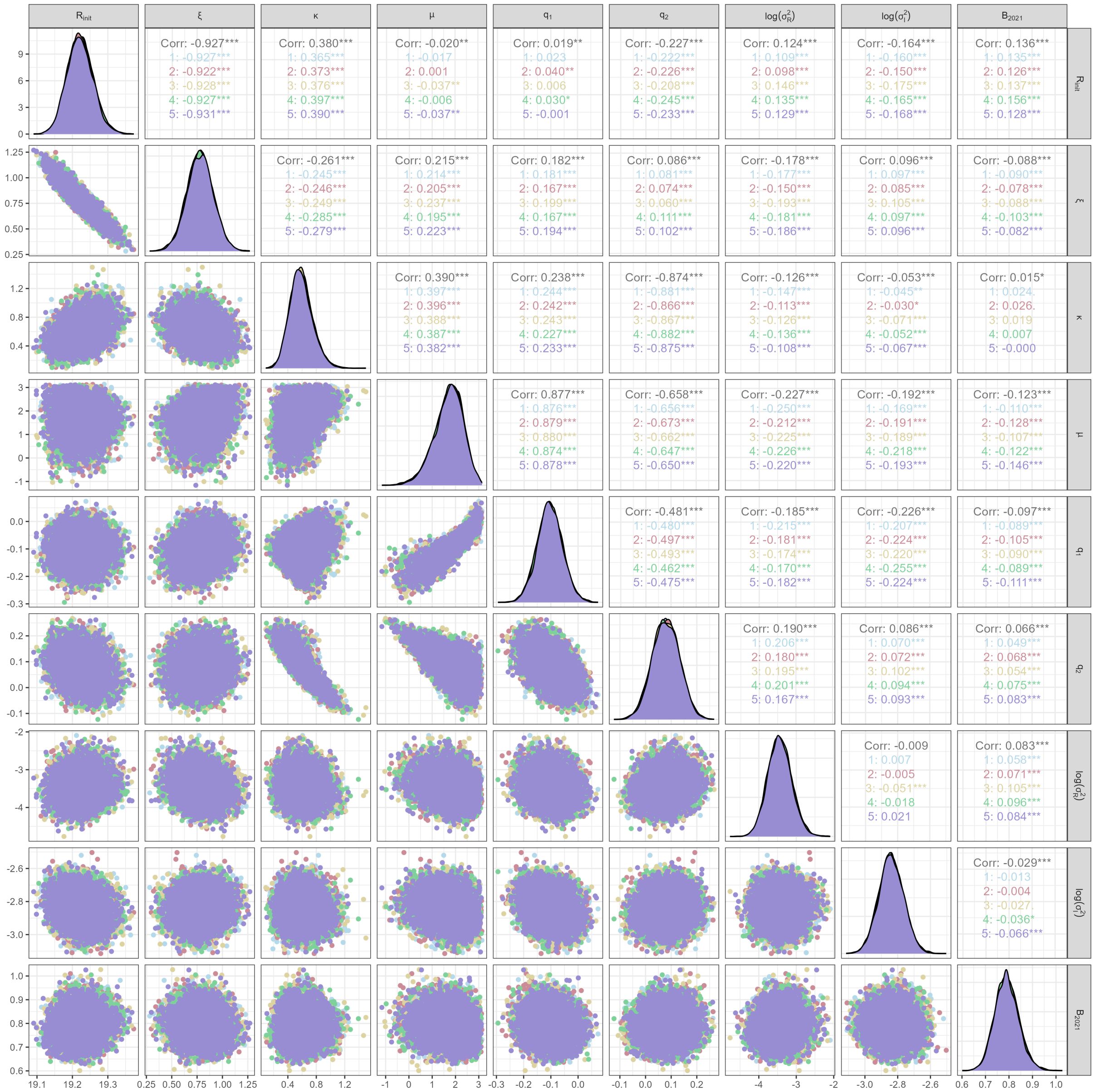


Figure B.22: Parameter correlations for east coast tiger prawns , scenario 1

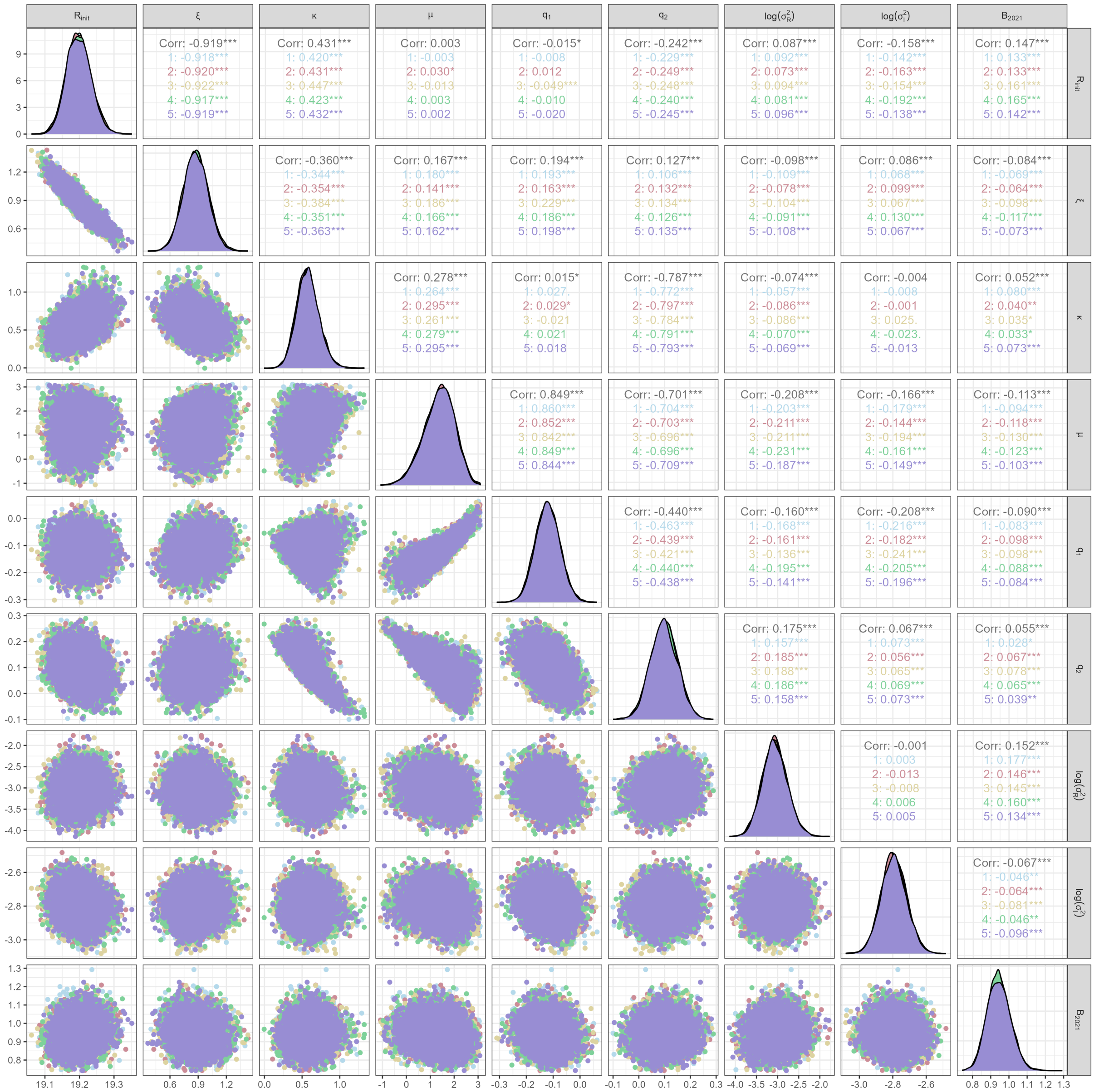


Figure B.23: Parameter correlations for east coast tiger prawns , scenario 2

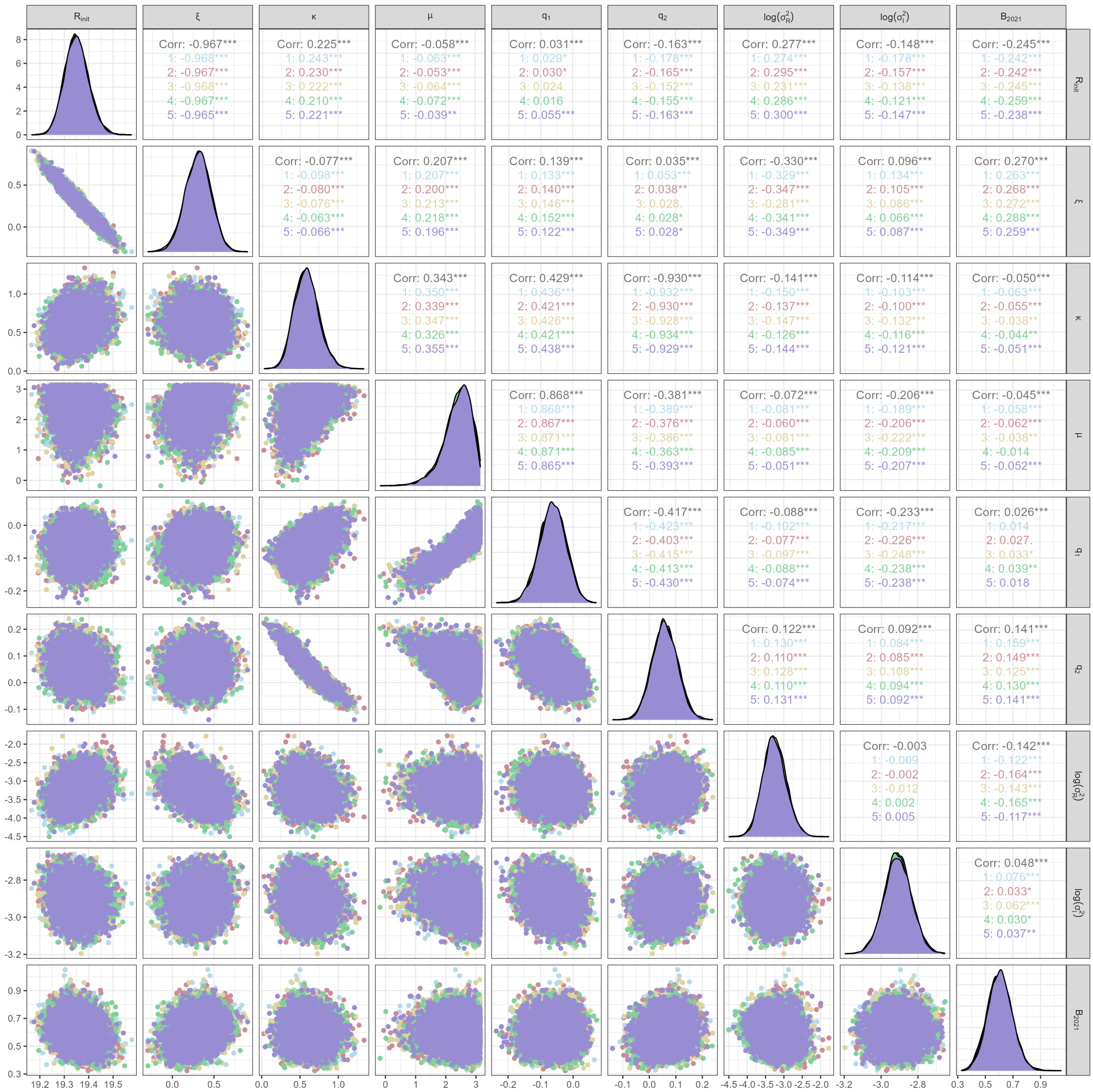


Figure B.24: Parameter correlations for east coast tiger prawns , scenario 3

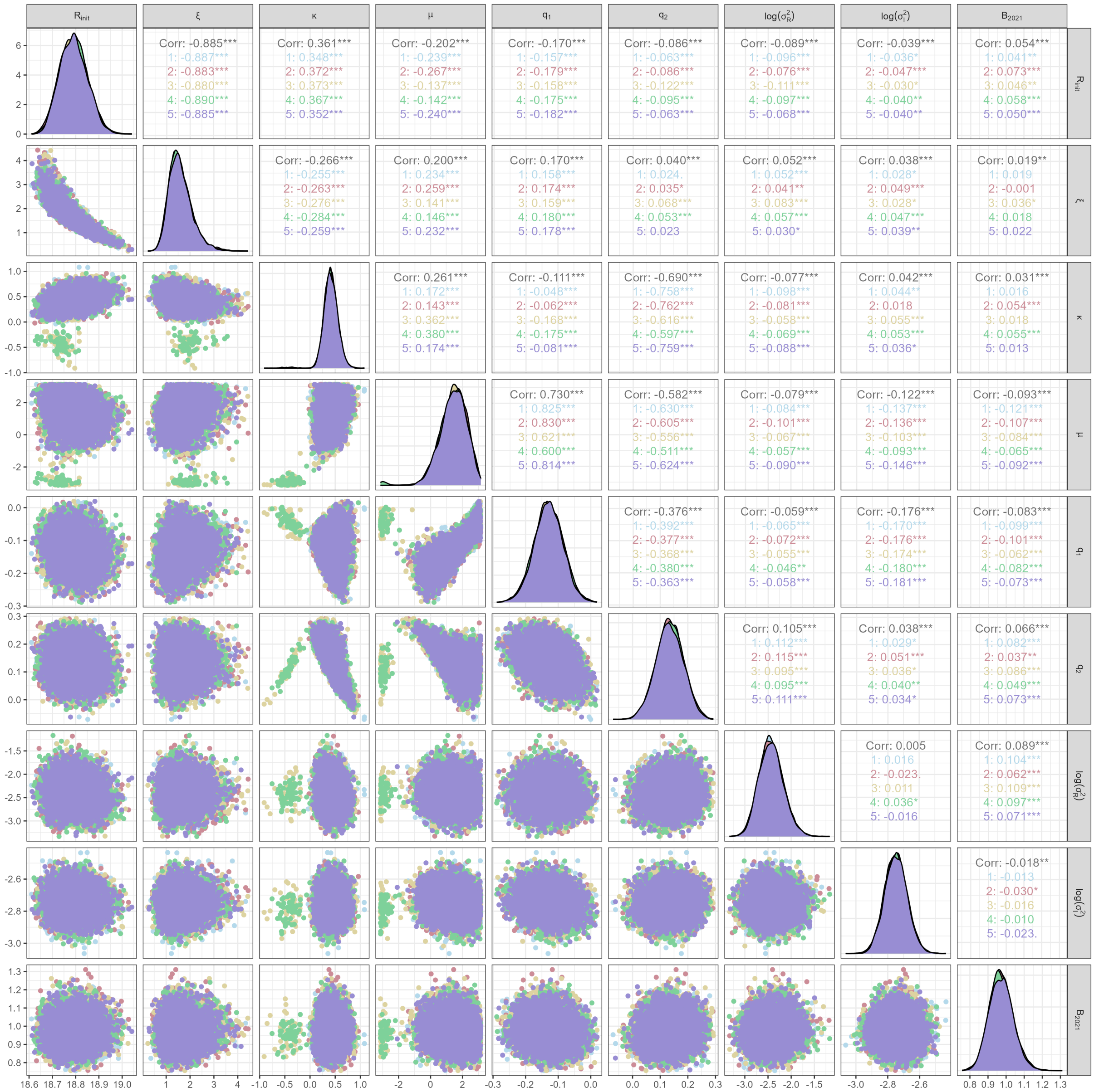


Figure B.25: Parameter correlations for east coast tiger prawns , scenario 4

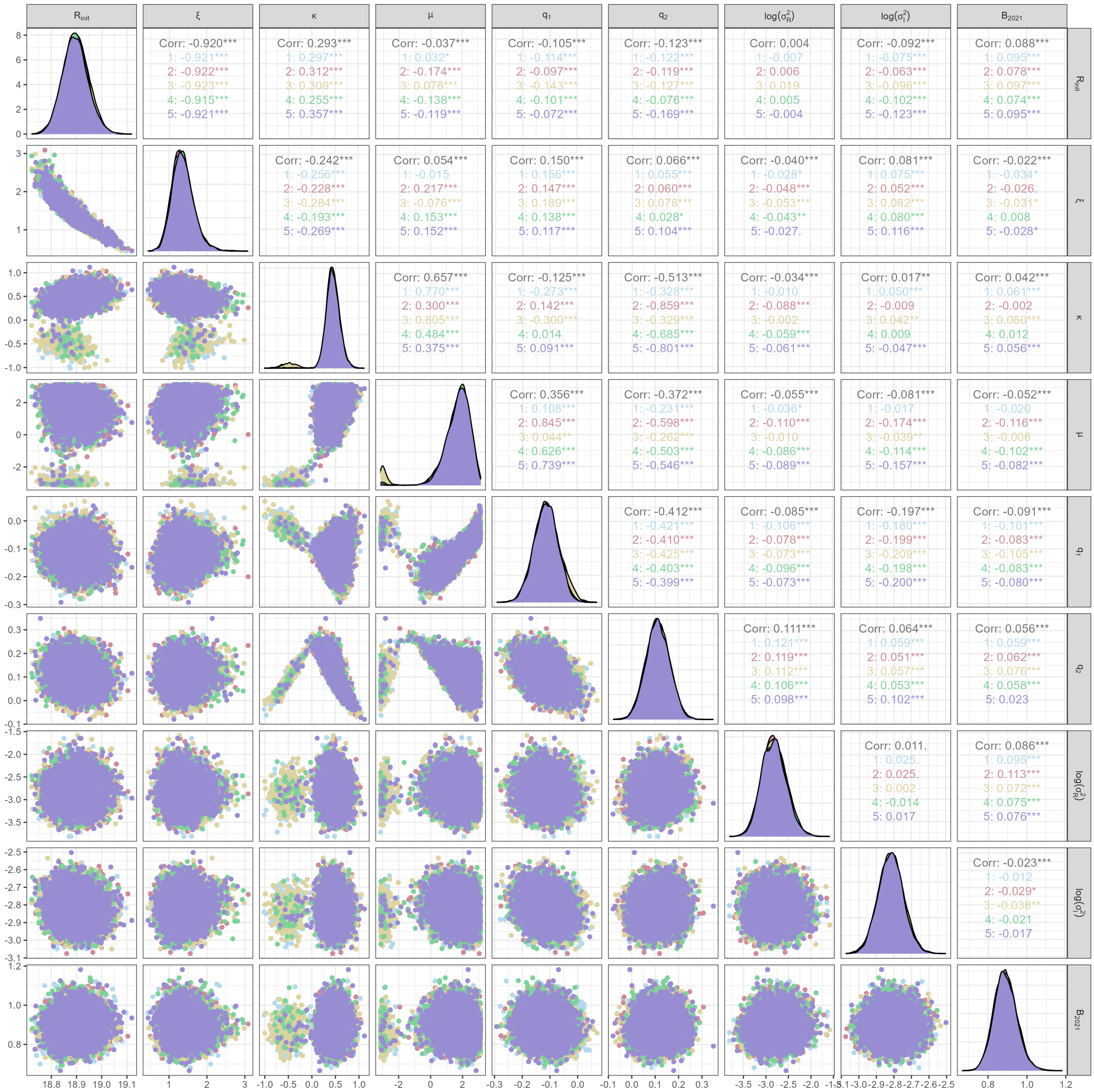


Figure B.26: Parameter correlations for east coast tiger prawns , scenario 5

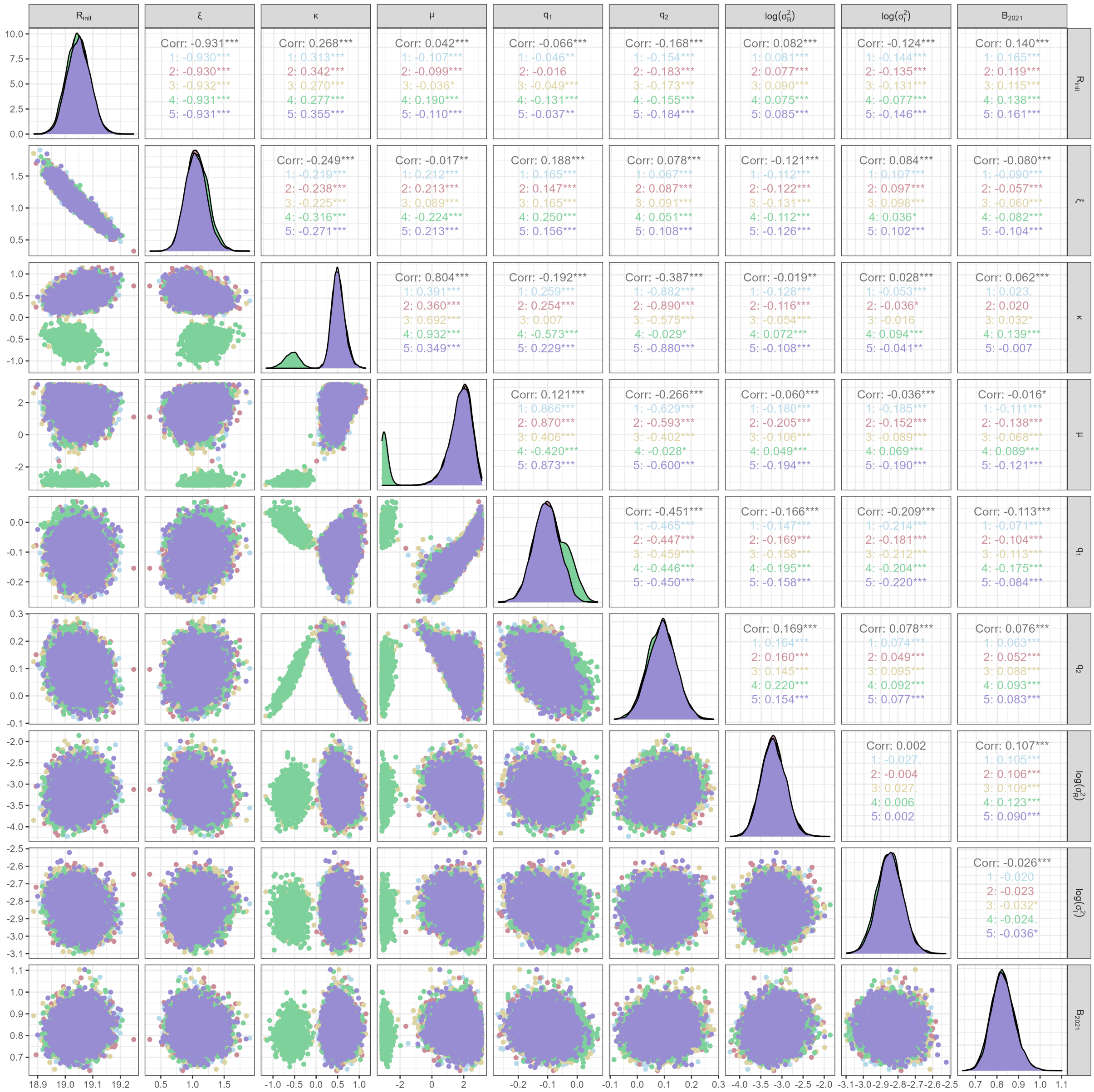


Figure B.27: Parameter correlations for east coast tiger prawns , scenario 6

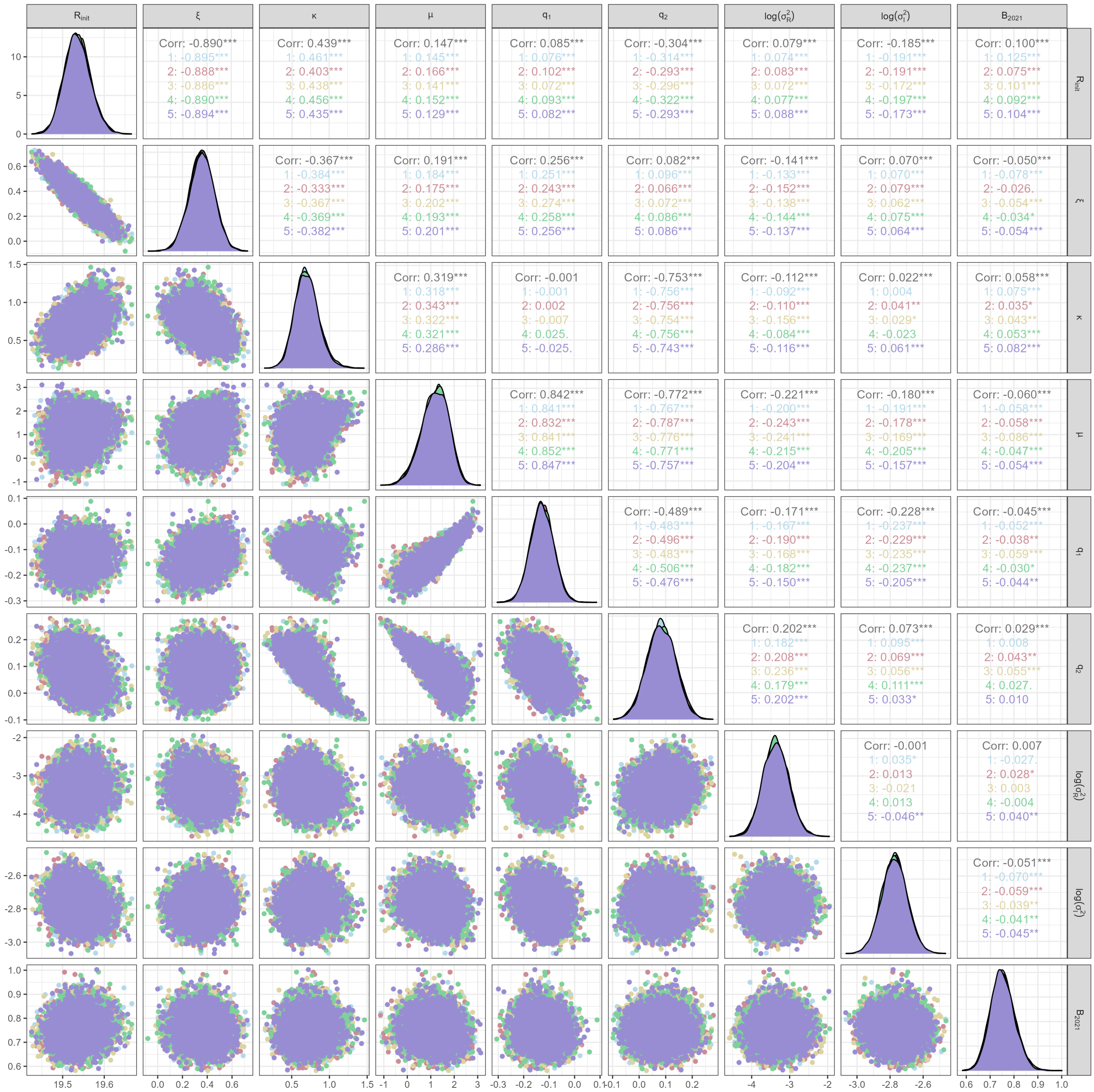


Figure B.28: Parameter correlations for east coast tiger prawns , scenario 7

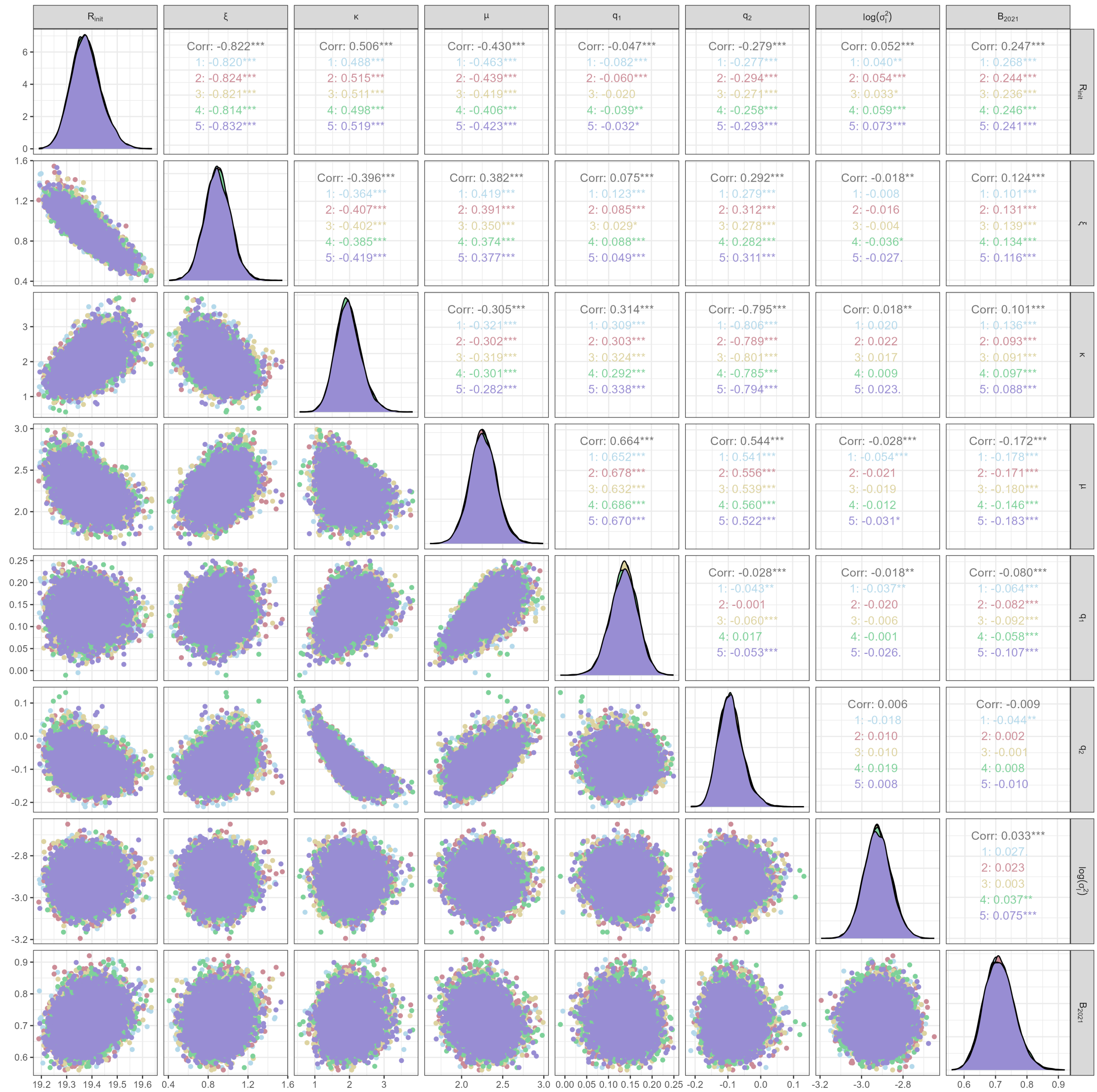


Figure B.29: Parameter correlations for east coast tiger prawns , scenario 8

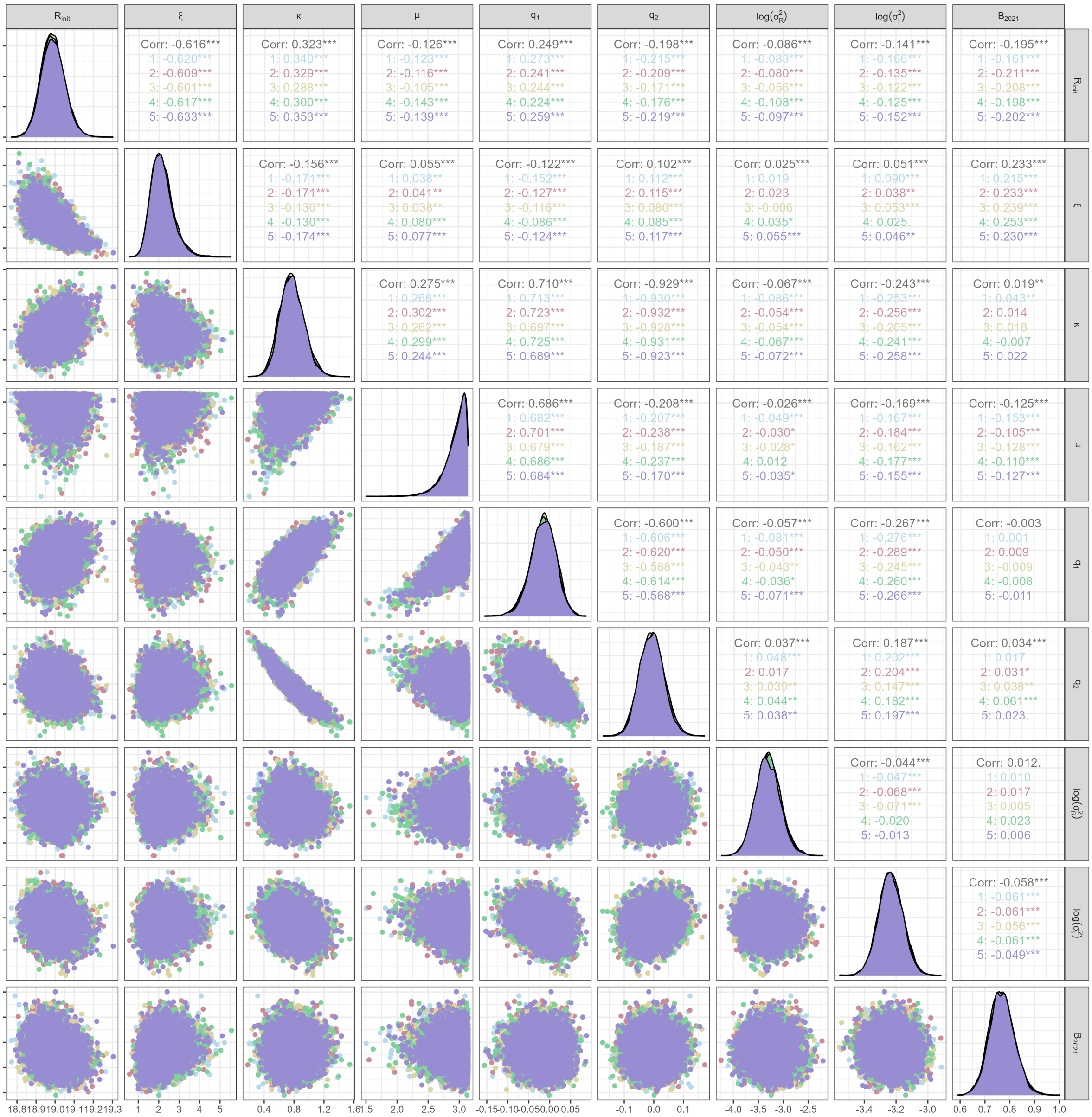


Figure B.30: Parameter correlations for east coast tiger prawns , scenario 9

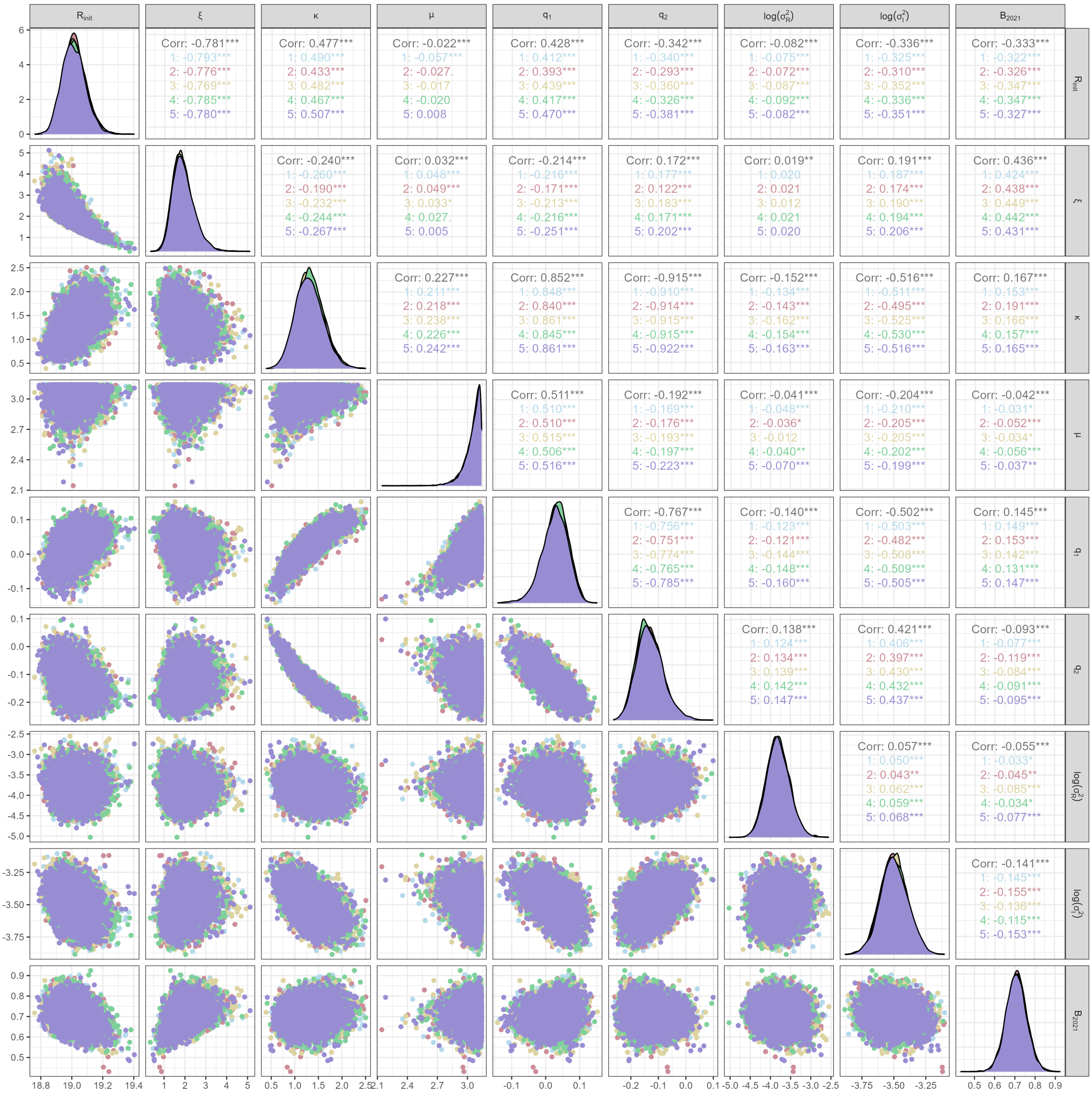


Figure B.31: Parameter correlations for east coast tiger prawns , scenario 10

B.2 Scenario outputs

Scenario 6 showed a higher than desirable $\hat{R}$ value for the parameters μ and k (Figure B.1). These effects can also be noted in the posterior density plots, trace plots and correlation plots (Figures B.7, B.17 and B.27). However, as these bimodal effects resolved early in the MCMC run and these parameters are cyclic in nature this was not a concern.

B.2.1 Sensitivity test

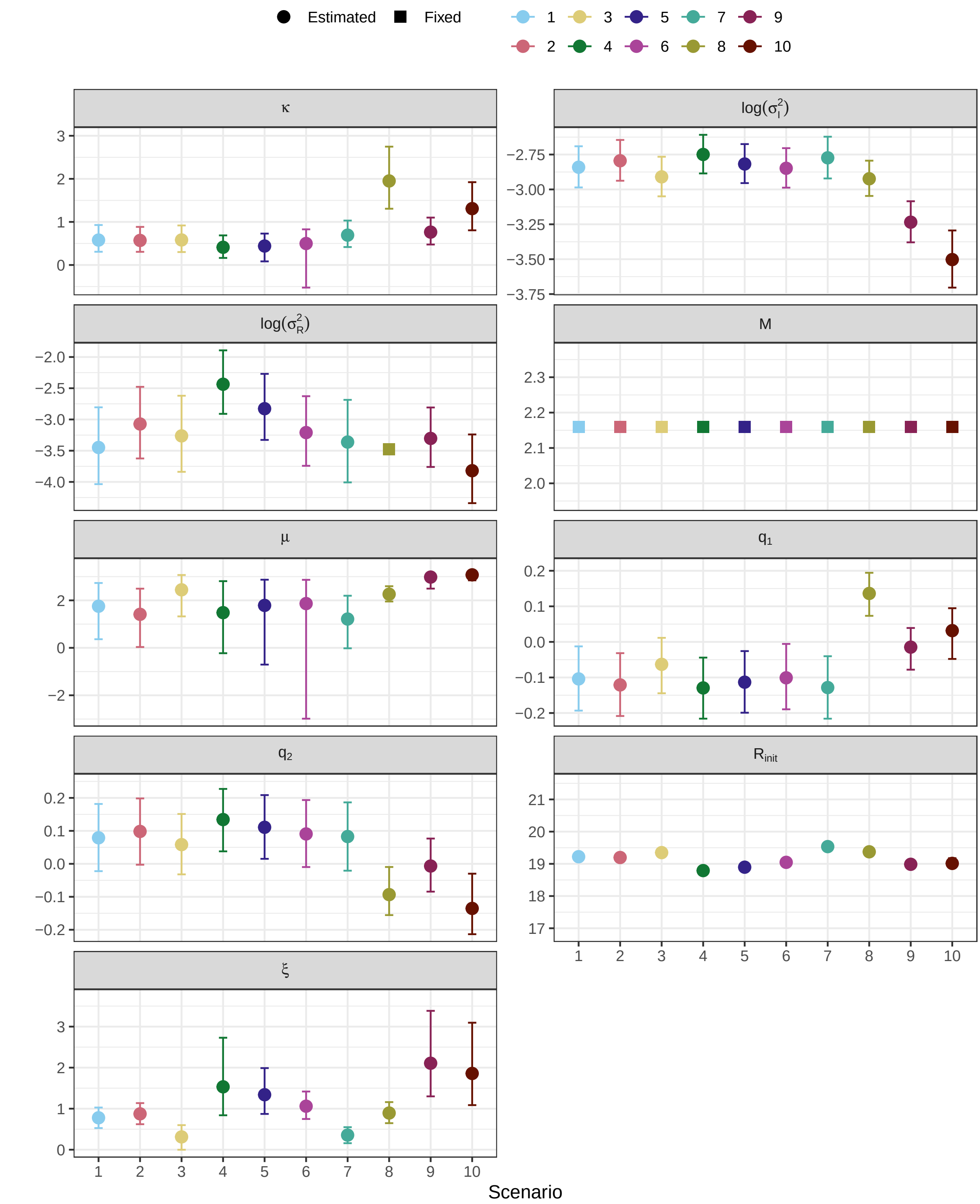


Figure B.32: Comparison of parameter estimates among scenarios for east coast tiger prawns —parameters were described in Section 2.5.3

B.2.2 Biomass

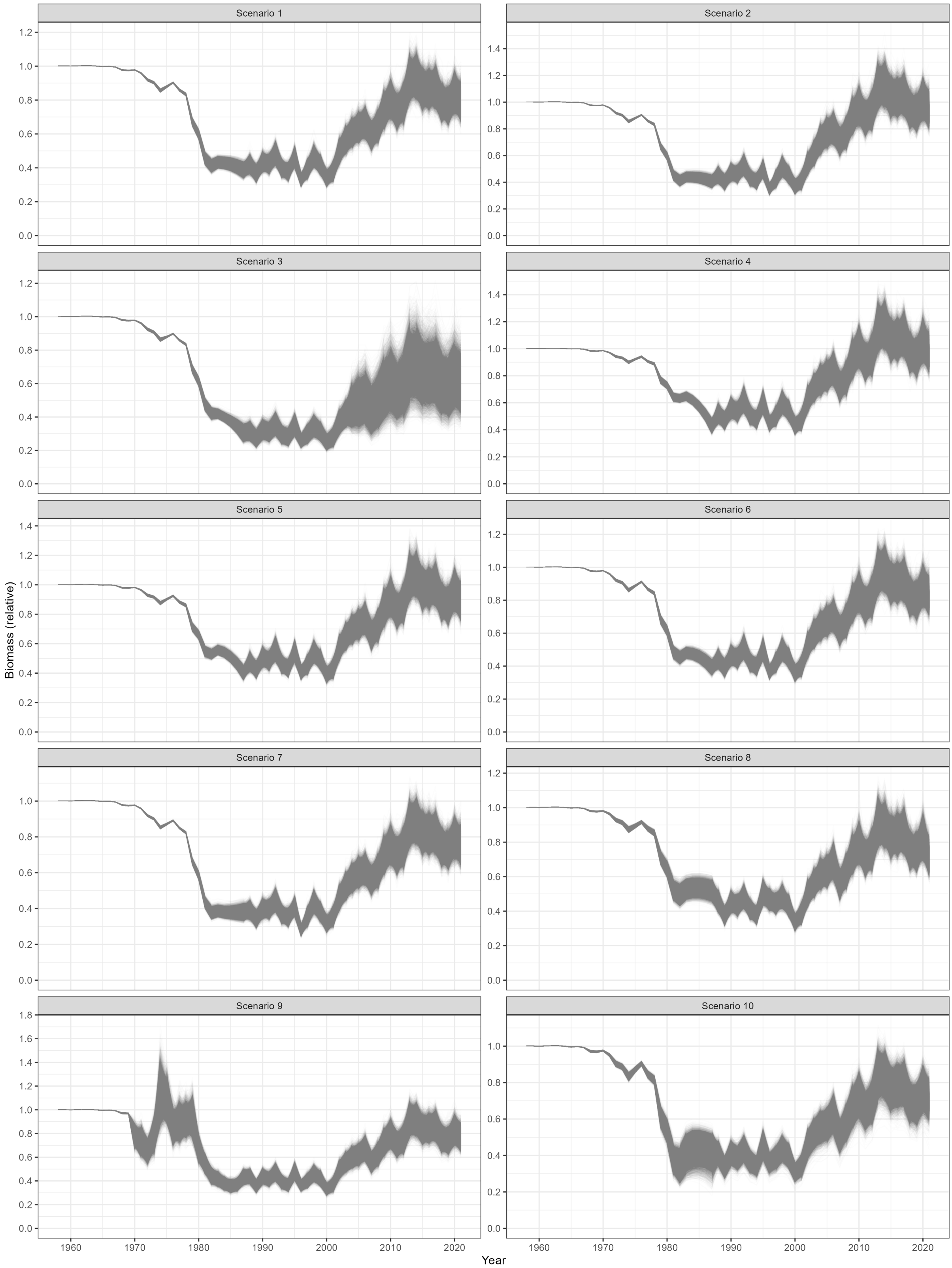


Figure B.33: Predicted biomass trajectory relative to unfished for tiger prawns, from 1958 to 2021 for each scenario—grey lines represent individual MCMC samples

B.2.3 Abundance indices

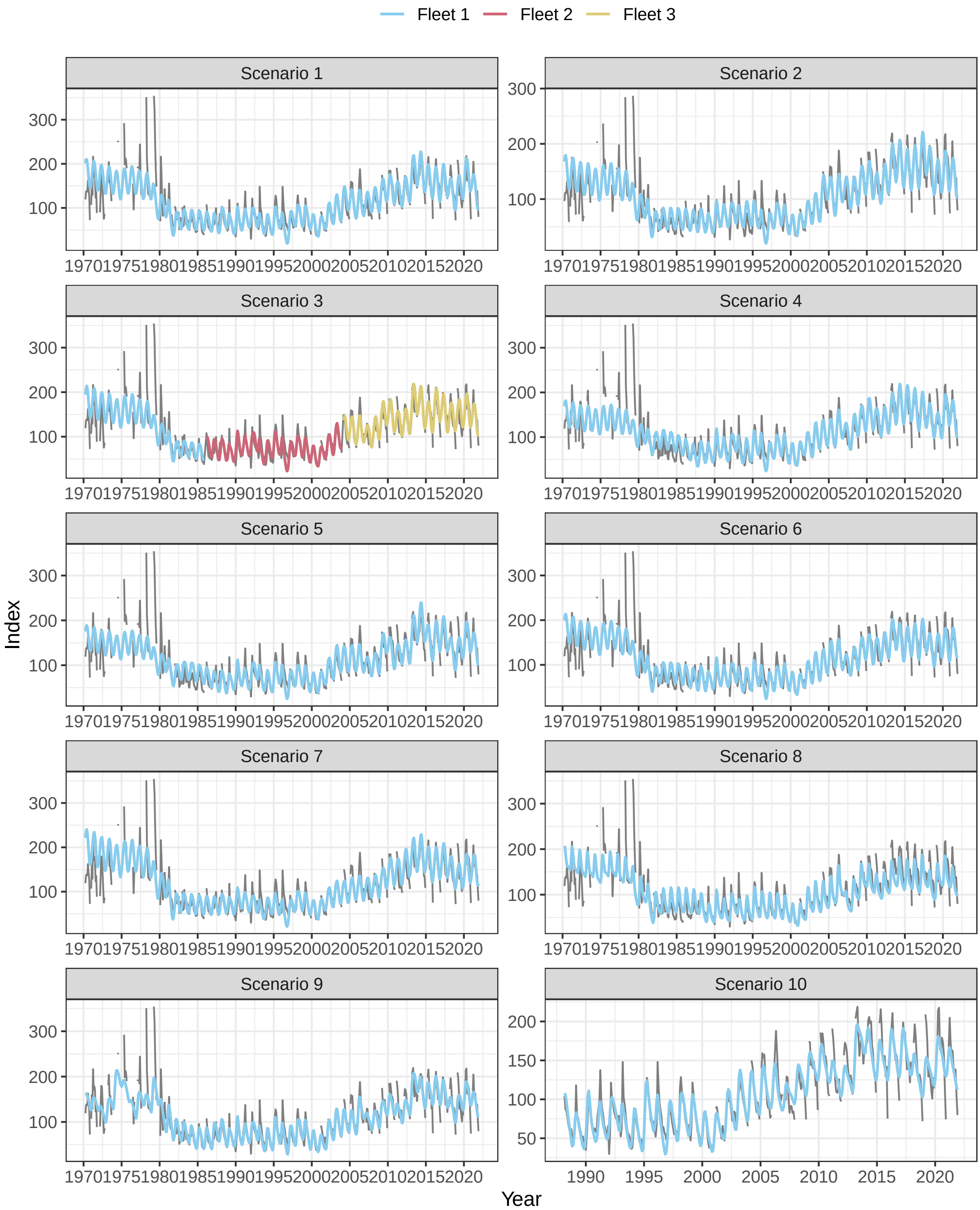


Figure B.34: Model predictions (blue line) to catch rates for east coast tiger prawns for each scenario

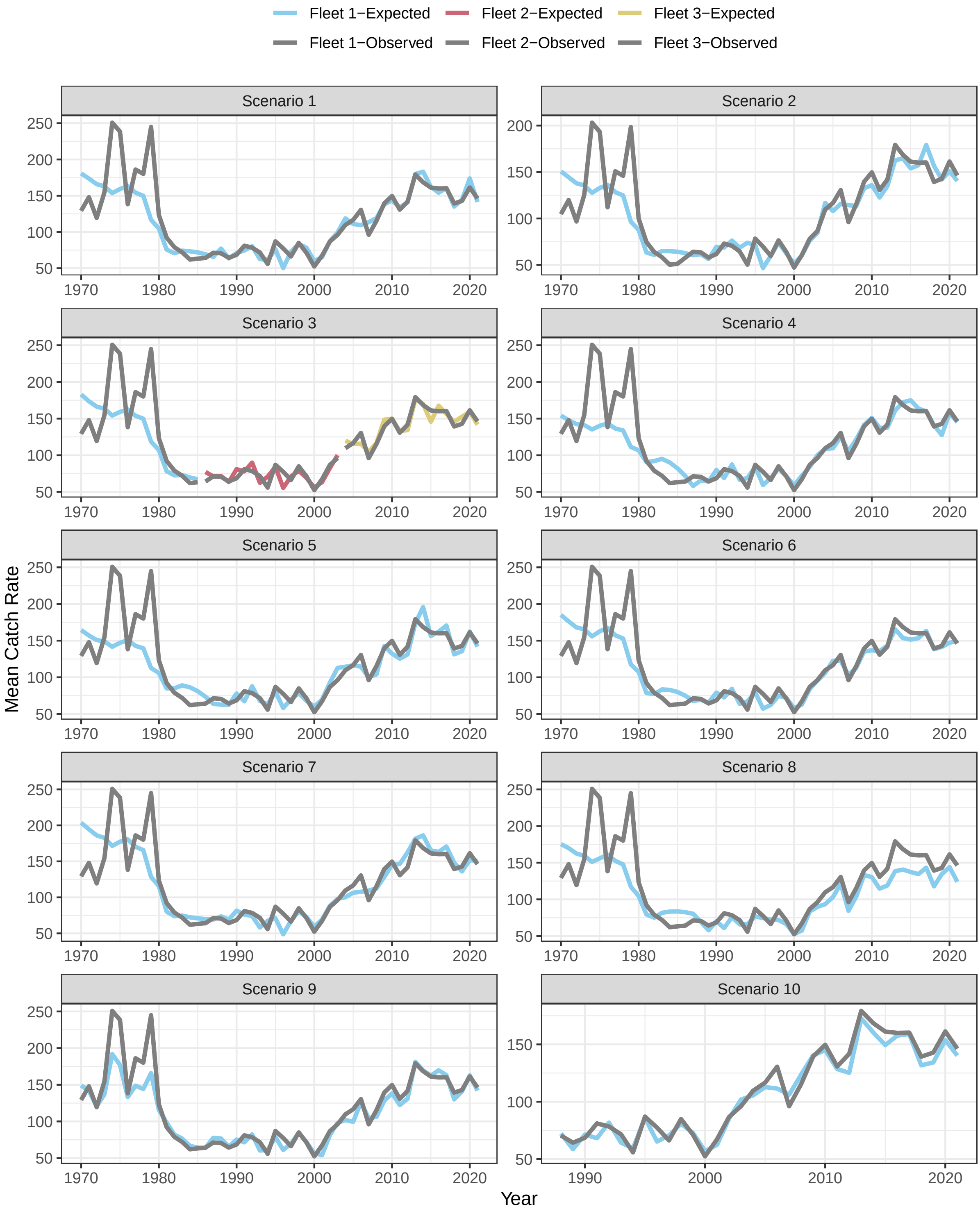


Figure B.35: Model predictions (blue line) to catch rates for east coast tiger prawns for each scenario, aggregated annually

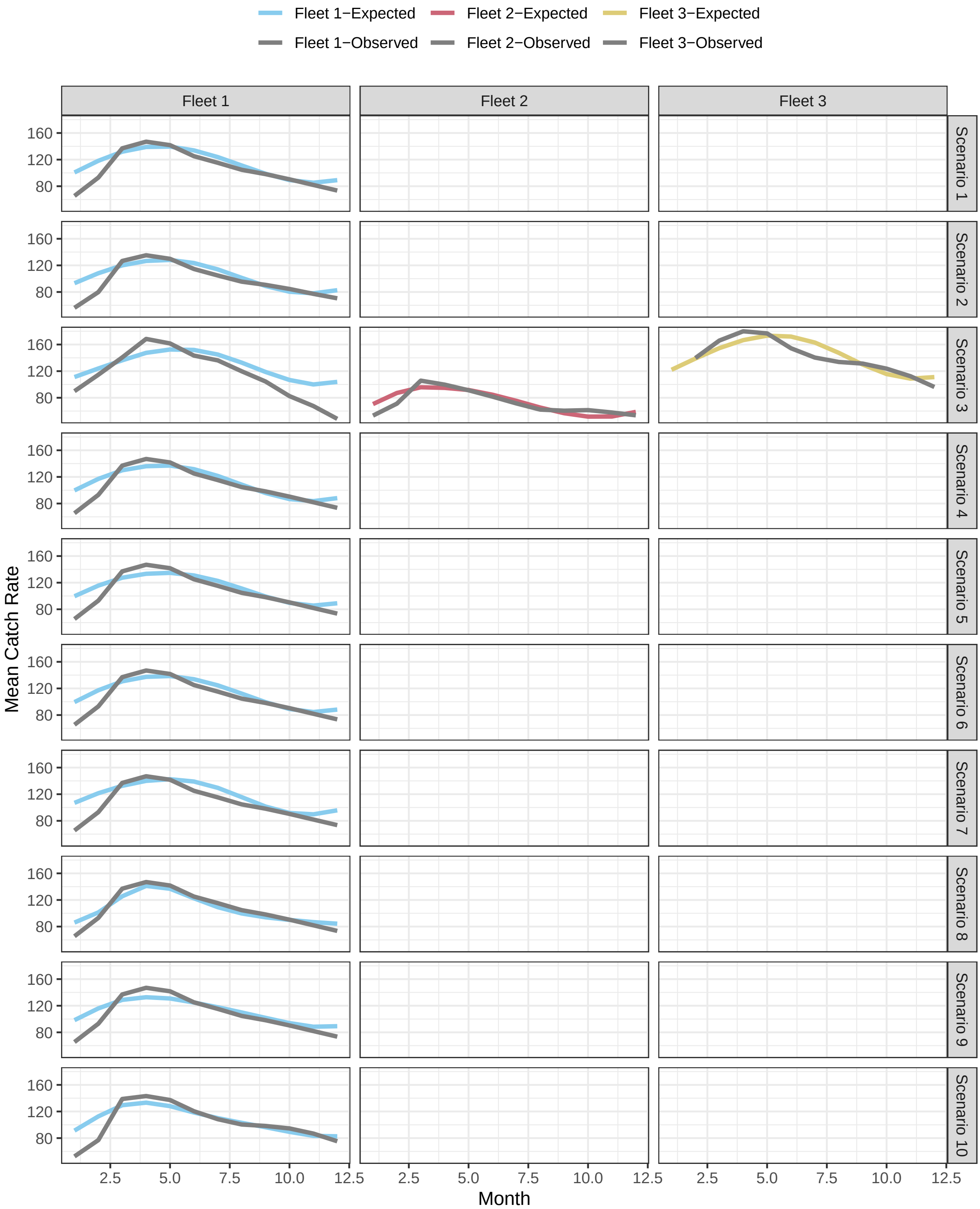


Figure B.36: Model predictions (blue line) to catch rates for east coast tiger prawns for each scenario, aggregated monthly

B.2.4 Stock-recruit curve

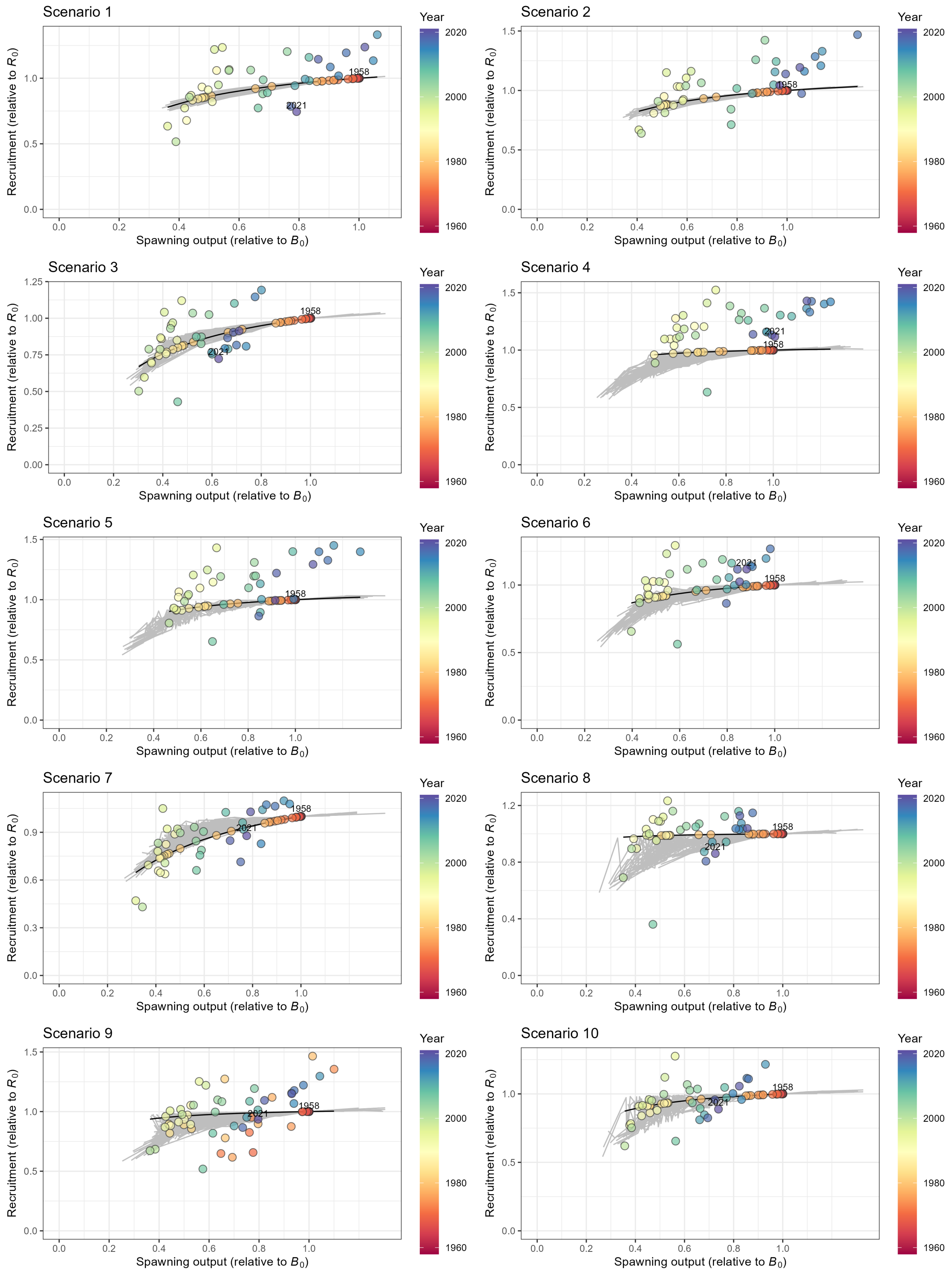


Figure B.37: Stock-recruit curve for east coast tiger prawn by spawning output for each scenario—point colors indicate year, with warmer colors indicating earlier years and cooler colors in showing later years

B.2.5 Recruitment deviations

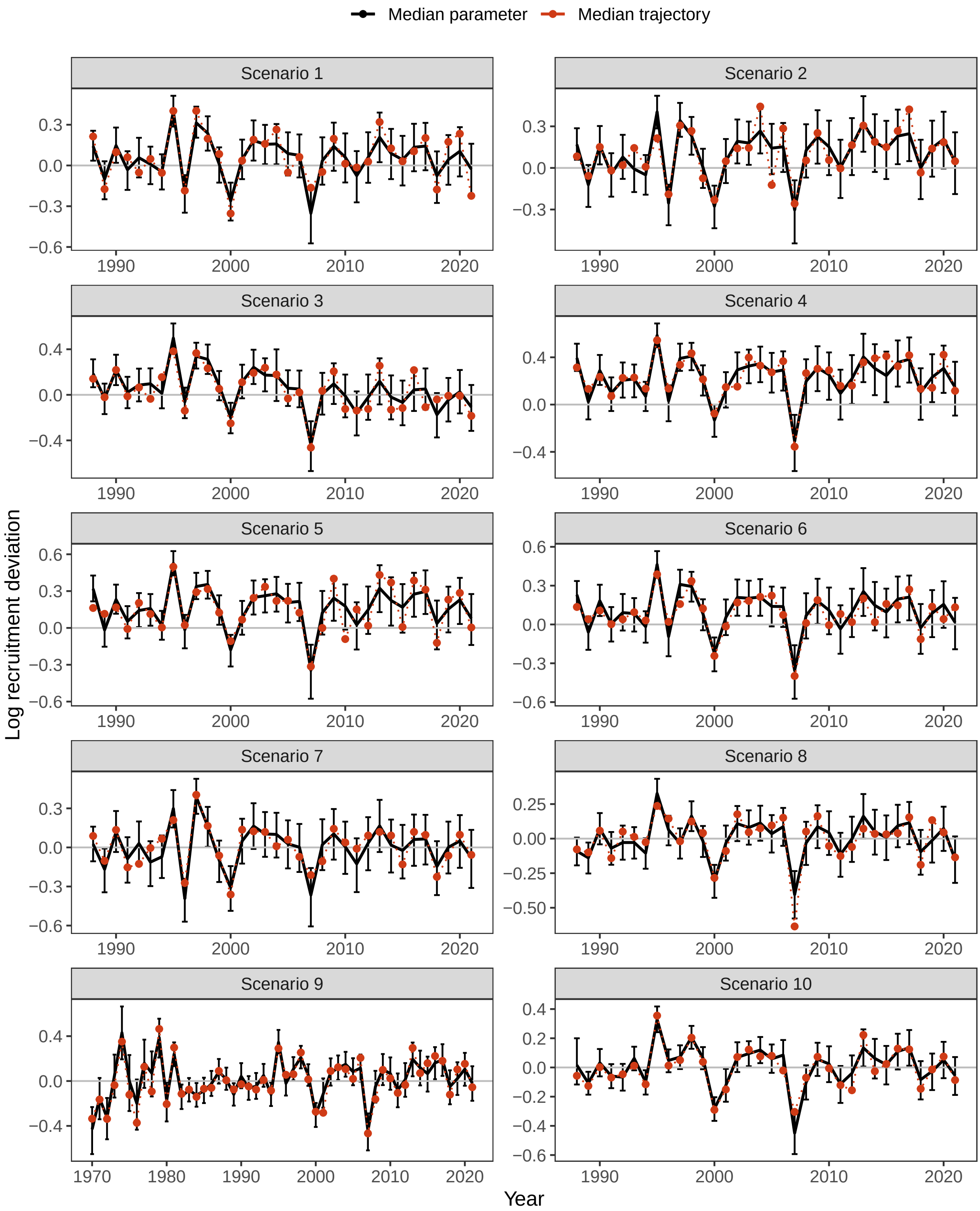


Figure B.38: Recruitment deviations with 95% confidence intervals for east coast tiger prawns for each case

B.2.6 Seasonal recruitment

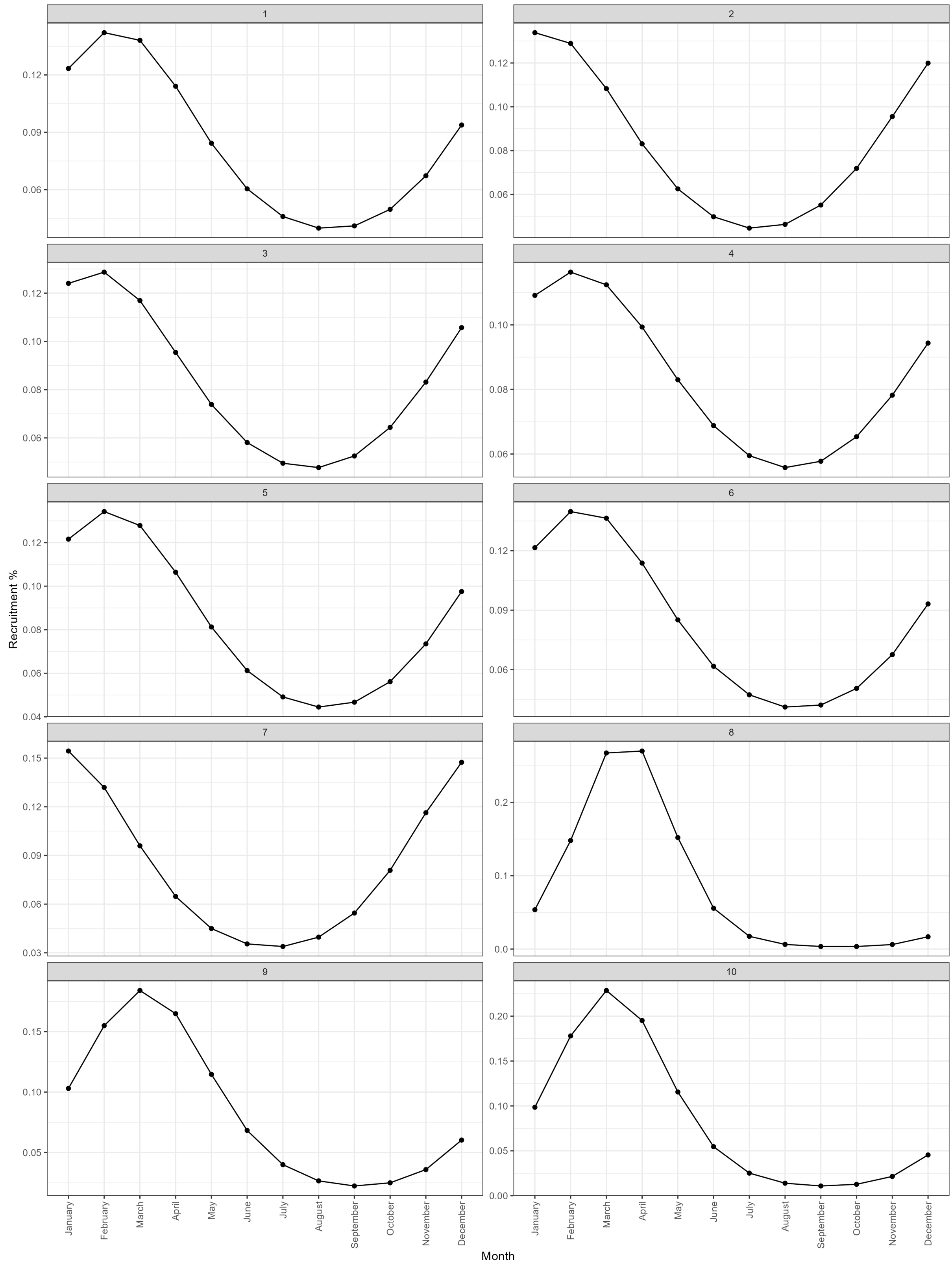


Figure B.39: Model estimated recruitment distribution of tiger prawns on the east coast of Queensland for each scenario—model estimated recruitment once per year and a distribution pattern for how recruitment should be apportioned to each month

B.2.7 Seasonal catchability

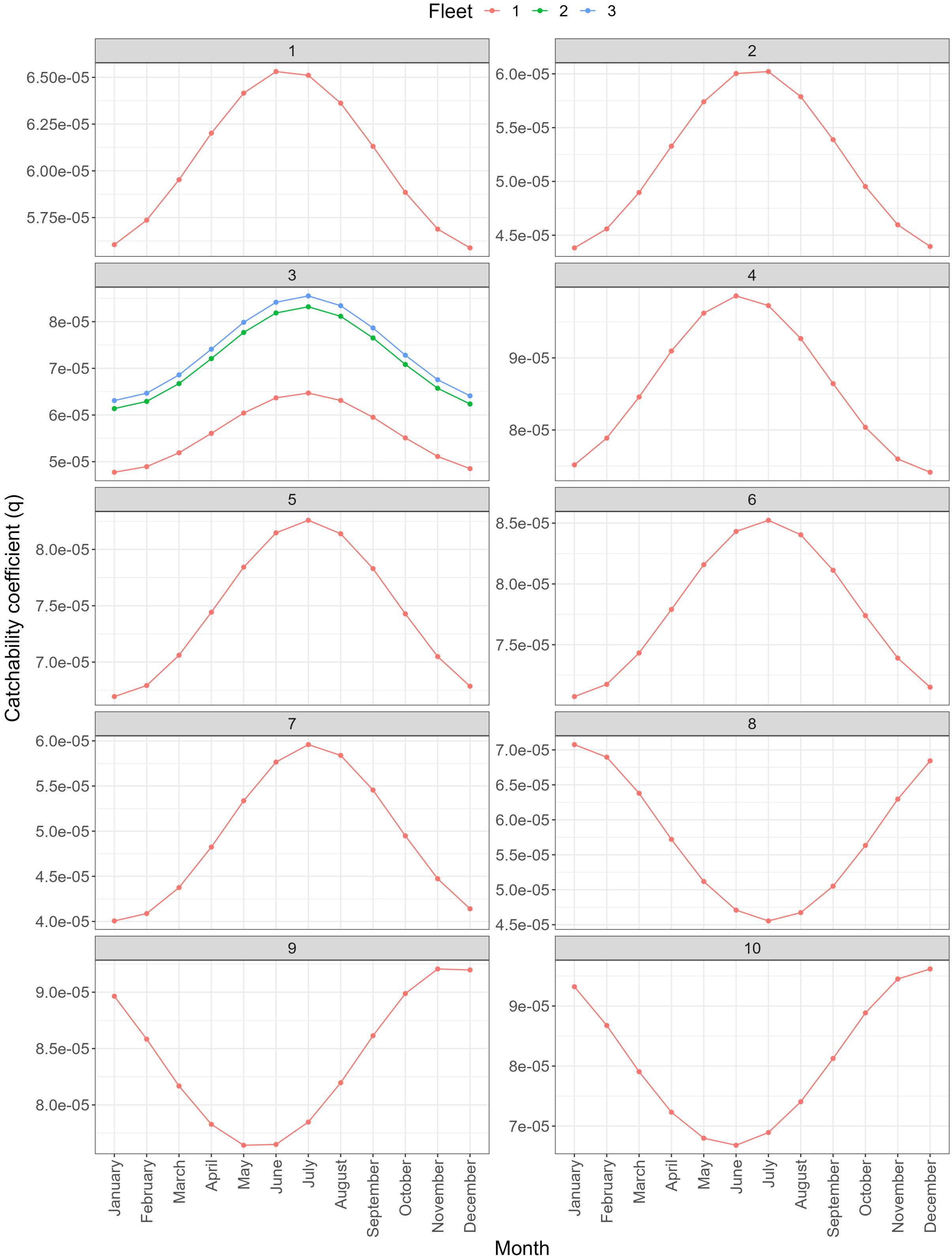


Figure B.40: Model estimated seasonal catchability of tiger prawns on the east coast of Queensland for each scenario

B.2.8 Fishing mortality

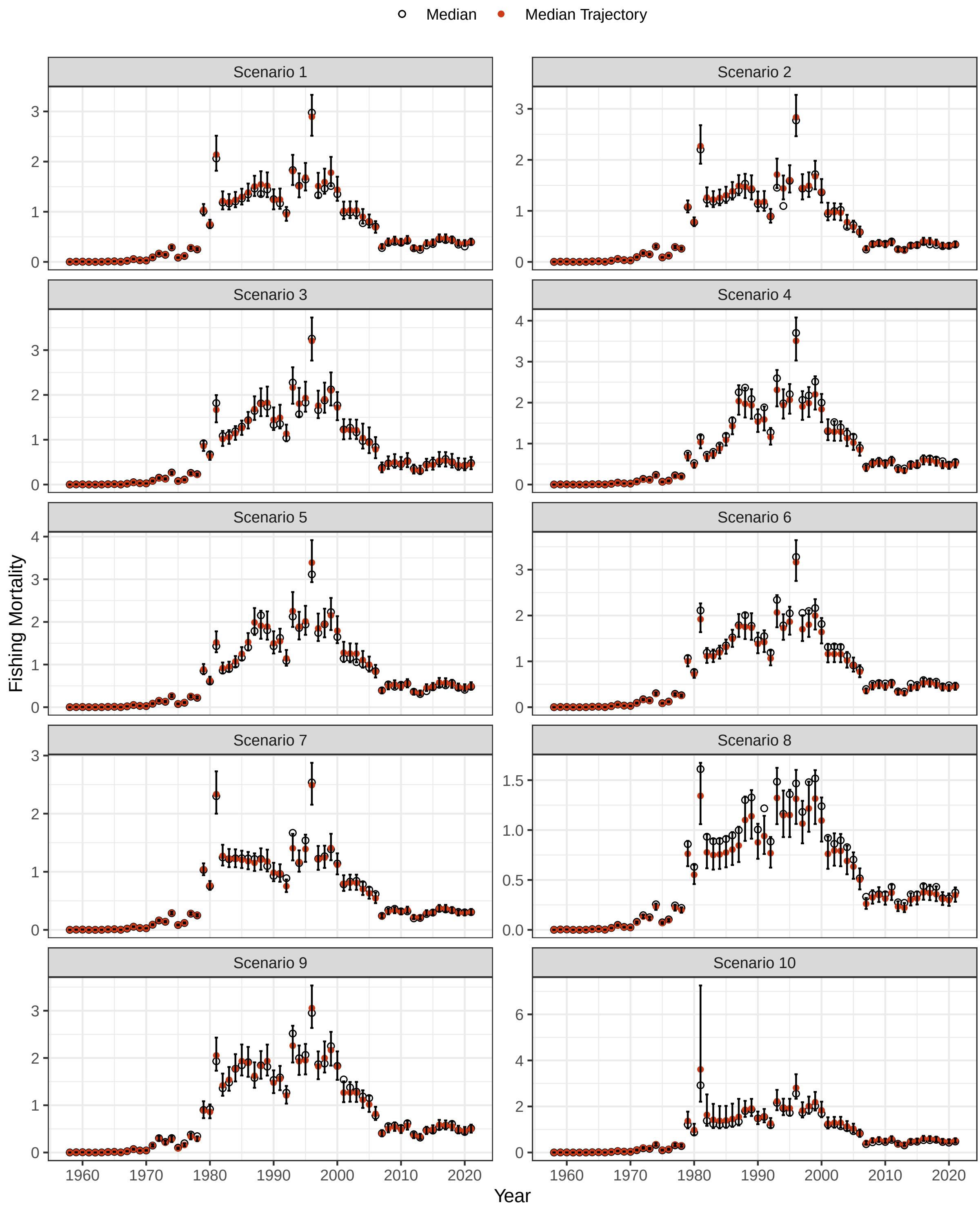


Figure B.41: Time series of fishing mortality ratio (F/F_{MSY}) for each scenario for east coast tiger prawns

B.2.9 Phase plot

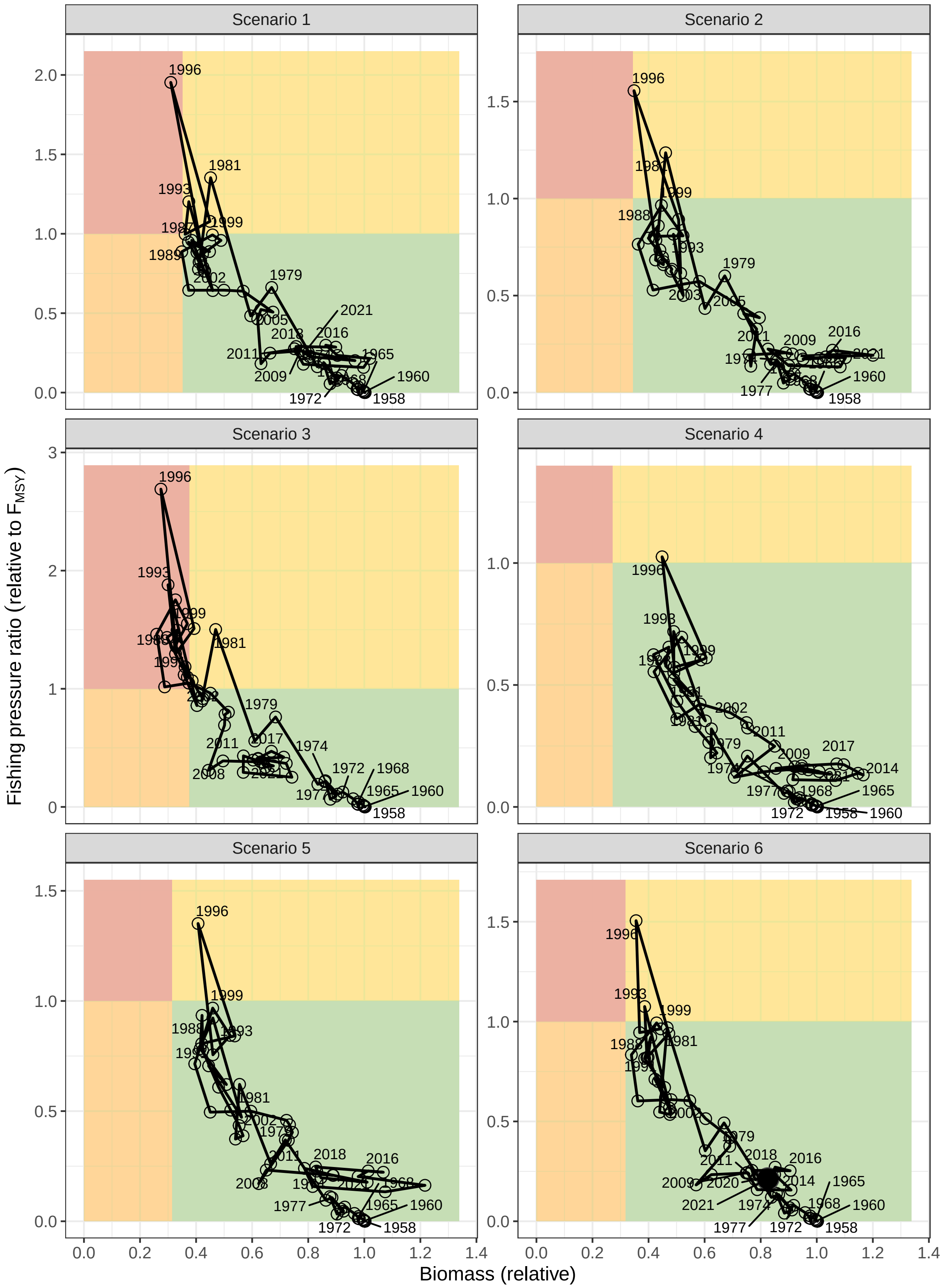


Figure B.42: Annual trajectory of fishing pressure ratio relative to biomass for east coast tiger prawns for scenarios 1–6—x-axis separation colour occurs at B_{MSY} and y-axis separation colour occurs at F_{MSY}

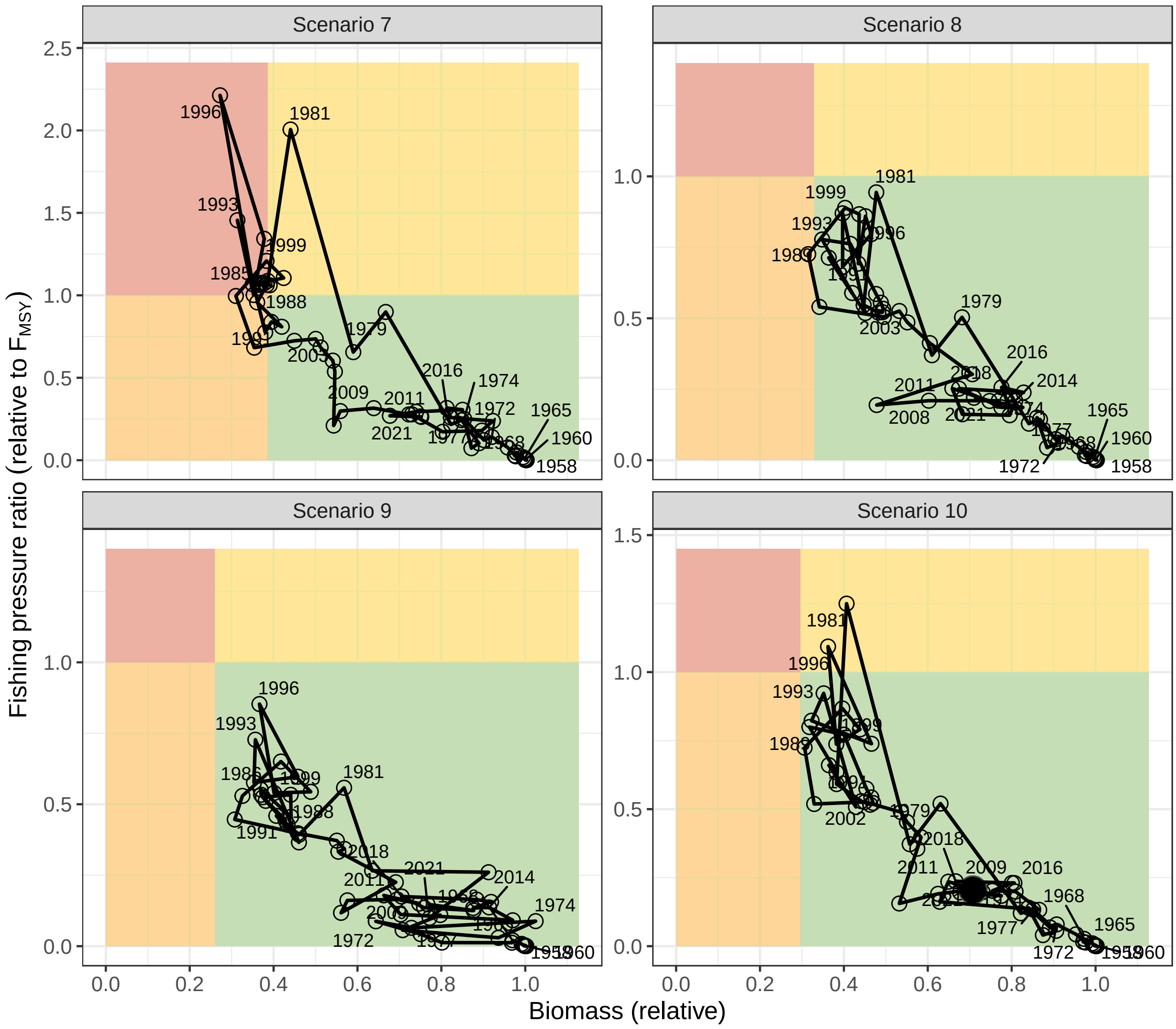


Figure B.43: Annual trajectory of fishing pressure ratio relative to biomass for east coast tiger prawns for scenarios 7–10—x-axis separation colour occurs at B_{MSY} and y-axis separation colour occurs at F_{MSY}

B.2.10 Yield curve

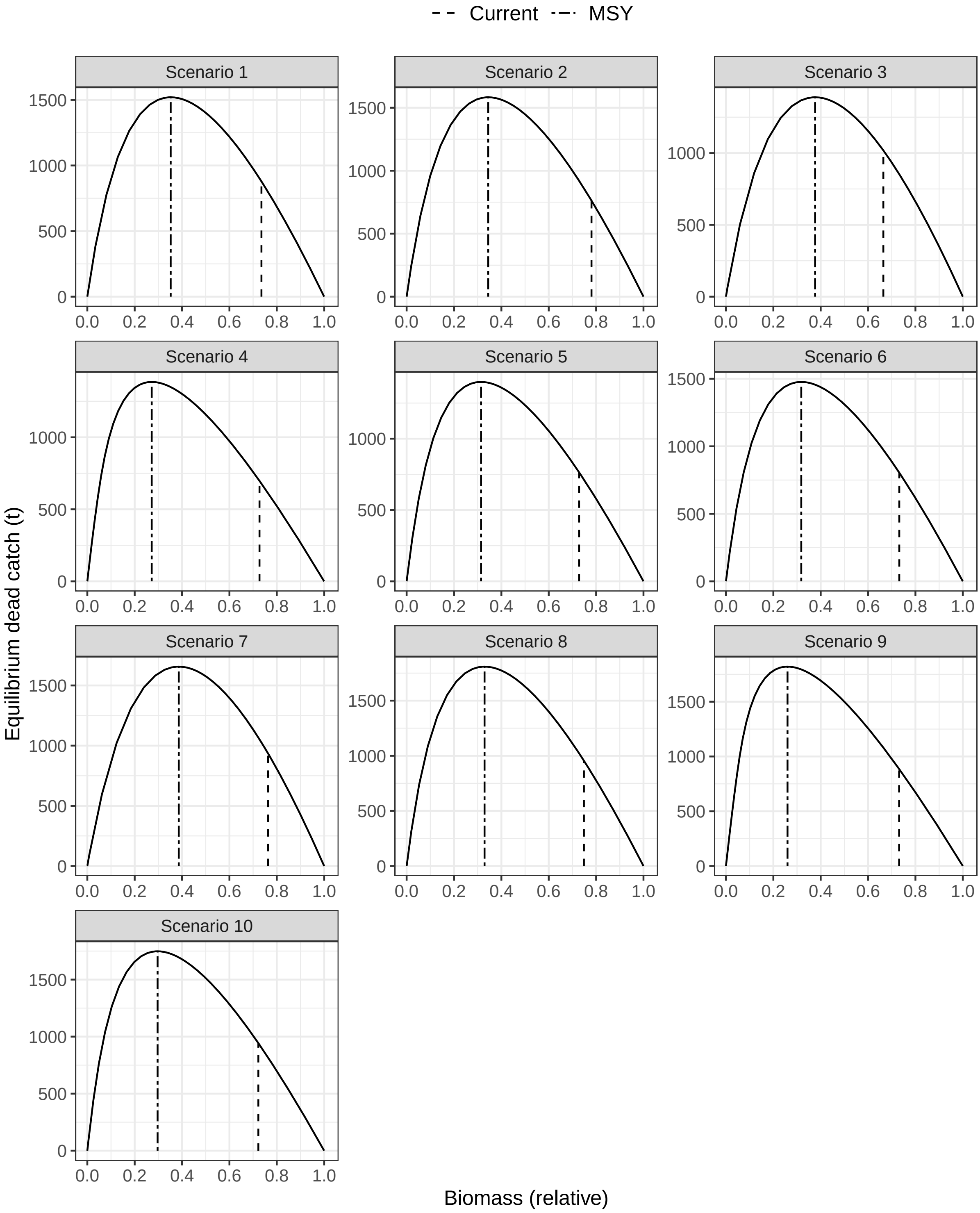


Figure B.44: Equilibrium yield curves for east coast tiger prawns —all scenarios

Appendix C Industry feedback and improvements to process

Industry feedback following Helidoniotis (2021) has been combined with internal review feedback and used to inform a checklist of topics to be addressed or improved for this assessment.

C.1 General feedback

- **Industry involvement on project team.** Following this feedback, from mid-2022, representatives from industry have been included as project team members on all Queensland Fisheries assessments providing valuable advice and knowledge about the fishery. For this assessment, industry had two representatives on the project team (Appendix D).
- **Focus on stock status** This stock assessment report focuses on biological stock status, hence the headline outputs being simply 'biomass level' and 'biomass direction'. How these biologically focussed models are used to inform management recommendations for a complex multi-species fishery like the ECOTF is recognised as best placed in a separate body of work. Another aspect of this focus worth noting is that both DDUST and Stock Synthesis are catch-driven, and so fishing effort is only relevant through the catch rate standardisation process. Total effort is not needed and is therefore not reported on.
- **Assess the populations on the basis of genetic or reproductive connectivity where possible.** The genetic and reproductively connected stock was determined to be all east coast Queensland latitudes south of 11° S and north of 21° S, plus between 21° S and 22° S and west of 152.5° E. This was determined through literature research and project team discussions (Section 2.1.1, Appendix D.1).
- **Validity of the dynamic pool assumption (closed areas).** Closed areas have been identified and presented in Section 2.1.1. Various different techniques and methods were explored and discussed with the project team to address this. Most however, were discarded due to the geographical coarseness of historical data creating meaningless inputs to work with. The validity of the dynamic pool assumption was finally explored through Scenarios 1–3 in Section 2.5.5 and discussed in Section 4.4.2.
- **Validity of the early data.** Extended discussion of historical catch reconstruction occurred during project team meetings (Appendix D.2). The final procedure for historical reconstruction of harvest is outlined in Section 2.2.2 and discussed in Section 4.4.2.
- **Fish board conversion from multispecies bucket to tigers.** The method of proportioning historical harvest to each species was discussed with the project team (Appendix D.2) and presented in full in Section 2.2.2.
- **Handling uncertainty (more scenarios/priors).** Ten scenarios were run to investigate model uncertainty and sensitivity to fixed parameters and model assumptions. More detail can be found in Section 2.5.5.
- **Seasonal variation relevance to how the annual quantities are calculated.** Seasonal variation was accounted for in the model with a seasonal q (catchability) and seasonal recruitment (Section 2.5.3).

- **Handling of seasonal cpue highs/lows.** The model estimated a seasonal q (catchability) to help describe the seasonal pattern of catch rates and gain better fits to data (Section 2.5.3, Appendix B.2.3).

C.2 Fishing power

- **Fishing power north vs central.** As the population was assessed as a single reproductively connected stock, only one time series of fishing power was modeled (Section 2.3.3).
- **Relevance of the chain size variable.** Variables used in fishing power modelling were extensively discussed during project team meetings (Appendix D). The chain size variable was not included in fishing power modelling (Section 2.3.3, Appendix A.1.2).
- **Relevance of other gear variables for fishing power.** Variables used in fishing power modelling were extensively discussed during project team meetings (Appendix D). Further description on fishing power modelling can be found in Section 2.3.3 and Appendix A.1.2.
- **Data validation for gear.** Validation of gear data was not within the scope of this project, however this has been noted as important future work.

C.3 Catch rates

- **Skipper experience.** Differing boat marks are incorporated into the catch rate standardisation which to some extent reflects differing skipper experience. The use of explicit skipper experience in the catch rate standardisation was discussed in project team meetings, however it was difficult to determine a metric for skipper experience and was left for future work (Section 4.3).
- **The ratio of tigers in the catch over time.** A targeting analysis was performed for tiger prawn with its associated species. The results of this targeting analysis was entered into the catch rate standardisation as a model term (Section 2.3.2).
- **How the 2004 RAP has been handled.** The catch rate standardisation incorporated as a model term, the fraction of the grid that was open to fishing. This term changed through time as closures occurred (Sections 2.3.4 and 4.2). Scenarios 1–3 also explored the effects of fishery closures (Section 2.5.5).
- **Voluntary logbook sheets pre-1988.** Voluntary logbook sheets prior to 1988 (HTRAWL) were used to create an index of abundance (Section 2.3). They were not used for catch reconstruction as they did not include all fishers. While the model was fit to this index of abundance, recruitment deviations were not for the project team preferred scenario. A scenario with recruitment deviations fit to the start of the HTRAWL time series, as well as a scenario which excluded HTRAWL data altogether, were also performed (Sections 2.5.5 and 4.2).
- **Multi-species effects.** A targeting analysis was performed for tiger prawn with its associated species. The results of this targeting analysis was entered into the catch rate standardisation as a model term (Section 2.3.2).
- **Influence of red spot and bugs on gear and effort allocation.** Effort allocation is not considered in this assessment or used for catch rate standardisation (Appendix C.1 point 2). However, an analysis on gear allocation was performed and gear plots have been updated (Appendix A.1.2).
- **More clarity on effort and targeting in general.** Total effort is not considered in this assessment (Appendix C.1 point 2). A targeting analysis was performed and included as a term in the catch rate standardisation (see Section 2.3.2).
- **Presentation of the seasonal lunar influence.** This is presented in Figure A.6.
- **Rainfall data.** Rainfall data was not used for this assessment and was left for future work (Section 4.3).

- **Impact of emergence of mother-shipping.** The impact of mother-shipping was left for future work (Section 4.3).

C.4 Biological

- **Growth.** Growth parameters used in the model resulting from research, data and project team discussions are presented in Section 2.4.

Appendix D Project team decisions

Project teams form an important part of the stock assessment process by providing guidance from experts from various disciplines relevant to the stock assessment. This approach ensures scientific validation and increases transparency. From mid-2022, representatives from industry were included as project team members on all Queensland Fisheries assessments providing valuable advice and knowledge about the fishery.

The following sections of this appendix briefly describe decisions made by the project team for this assessment.

D.1 Spatial scope

The project team considered the spatial scope for this assessment to be all east coast Queensland latitudes south of 11° S and north of 21° S, plus between 21° S and 22° S and west of 152.5° E (Figure 2.1). This spatial stock boundary, except for the northern boundary, is the same as was used in O'Neill et al. (2006b). This decision was supported by high resolution vessel tracking data (for more detail see Section 2.1.1).

Discussion of literature regarding tiger and endeavour prawn movement resulted in a decision to exclude Torres Strait from the spatial scope of the assessment (Watson et al. 1993; Ward et al. 2006, see also Section 2.1.1 of this report).

- ***Meeting 2, Decision 1:*** *Use the work by O'Neill et al. (2006a) as template for segregating stocks and focus on stocks north of 22° South, use scenario 1 "Exclude south of 22°, different area for open and closed zones".*
- ***Meeting 3, Decision 1:*** *Torres Strait to be excluded from this assessment.*

D.2 Historical catch

The project team considered that FishBoard data did not capture the full harvest at the time. Historical catch reconstruction was therefore based on data for all of Queensland obtained from Hutchison (2015) page 102–103, Table 4. These data were then allocated regionally and by species as set out in Section 2.2.2. The ratio used for species allocation was adjusted so the red spot king prawn ratio was reduced by half as the red spot king prawn fishery was not well established before 1980.

- ***Meeting 2, Action 5:*** *Adjust the catch reconstruction for red spot. Halve the proportion of red spot and allocate to endeavour, tiger and other prawns.*
- ***Meeting 2, Decision 2:*** *Catch reconstruction to be based on Hutchison (with red spot adjusted) and include two further scenarios a 125% scenario and 75% scenario.*

D.3 Species split

'Tiger prawn' is a collective term for two species: brown tiger prawn (*Penaeus esculentus*) and grooved tiger prawn (*P. semisulcatus*). Logbook records do not specify if catch is comprised of *Penaeus esculentus*, *P. semisulcatus* or a mix of both, hence tiger prawns must be modeled collectively.

- ***Meeting 2, Decision 3:*** *Retain tiger prawn complex without separating into brown and grooved.*

D.4 Catch rates and fishing power

Extensive analysis of catch rates and fishing power was performed and discussed with the project team. Catch rates formulation and diagnostics are presented in Sections 2.3, 2.3 and Appendix A.1. Fishing power formulation and diagnostics are presented in Section 2.3.3 and Appendix A.1.2.

- ***Meeting 5, Decision 1:*** *Use fishing power estimates that utilise data up to 2021.*
- ***Meeting 5, Action:*** *Move forward with the catch rate analyses that have been done so far.*

D.5 Model scenarios

The project team were shown various diagnostics and model fits for a wide range of scenarios. From this a preferred scenario was chosen along with a suite of scenarios as outlined in Section 2.5.5.

- ***Meeting 5, Decision 2:*** *Project team agrees that discounts should be run as scenarios, in addition to a non-discounted scenario. For the discounted scenarios, project team yet to agree on the range of discount values or what method should be used to apply them.*
- ***Meeting 6, Summary of decisions:***
  - *150% catch reconstruction as preferred. The historical catch reconstruction scenarios to be included in reporting are 75%, 100%, 125% and 200%.*
  - *Continuous catch rates as preferred.*

Appendix E Bridging analysis

The delay-difference model used in this assessment comes from a package called DDUST (Appendix F) written in TMB (Kristensen et al. 2016). This model differs slightly in formulation to the past assessment (Helidoniotis 2021).

A bridging analysis has been performed here for two reasons:

- To show changes in model formulation
- So that differences between results and decisions made in this assessment can be compared with results from Helidoniotis (2021) had the same model package been used and the same project team decisions been made

This bridging analysis is performed with a final year of 2019 so that results can be compared easily with Helidoniotis (2021). Changes have been made incrementally to align with the formulation and decisions used for the current assessment. These changes are as follows:

1. The model formulation written in R (R Core Team 2020), data and settings used in Helidoniotis (2021) for the Northern region was run. Note that Helidoniotis (2021) assessed the stock in two regions (North and Central). The region with the largest harvest (North) has been chosen for this bridging analysis.
2. An extended fitting routine with more iterations was performed.
3. The upper bound for σ_R was increased to 0.5.
4. The steepness prior formulation was changed. Note that the TMB environment has difficulty with conditional statements that are derived from estimated parameters, hence a new formulation was required. This new formulation can be found in Appendix F.
5. Parameters for seasonal variation of q (catchability) were added to the model.
6. A prior was added for μ (the phase shift of the recruitment function).
7. A prior was added for k (the amplitude of the recruitment function).
8. The formulation for the monthly recruitment pattern was changed. The Bessel function used in Helidoniotis (2021) was problematic in the TMB environment so a simpler formulation was chosen.
9. Model inputs for weight at recruitment and pre-recruitment (w_r and w_{r-1}) were calculated from sampling data obtained over the years 1998–2009 (Fisheries Queensland 2012b).
10. A new value for ρ was input derived from the new values obtained for w_r and w_{r-1}.
11. A penalty for if the catch was greater that the recruits on any given time step was changed.
12. A new formulation for survivorship was used due to the TMB environment's difficulty with conditional statements.
13. The recruitment deviation start year was changed to 1988 to keep in line with decisions made for this assessment.
14. Changed formulation for catch rate and recruitment deviation log likelihood functions due to the TMB environment's difficulty with conditional statements.
15. The DDUST model was used (Appendix F).
16. Model data was changed to data input for this assessment (although truncated to 2019). Note that this data encompasses both North *and* Central regions.
17. The REDDUST model was used. This model is part of the DDUST package but differs in that it models the recruitment deviations as random effects (Appendix F).

18. The initial values for the parameters $\ln(R_0), q_1, q_2, \ln(\sigma_I^2), \ln(\sigma_R^2)$ were changed to reflect the project team preferred initial values. Note that this scenario uses maximum likelihood estimation and hence differs slightly from the final biomass presented throughout this report.

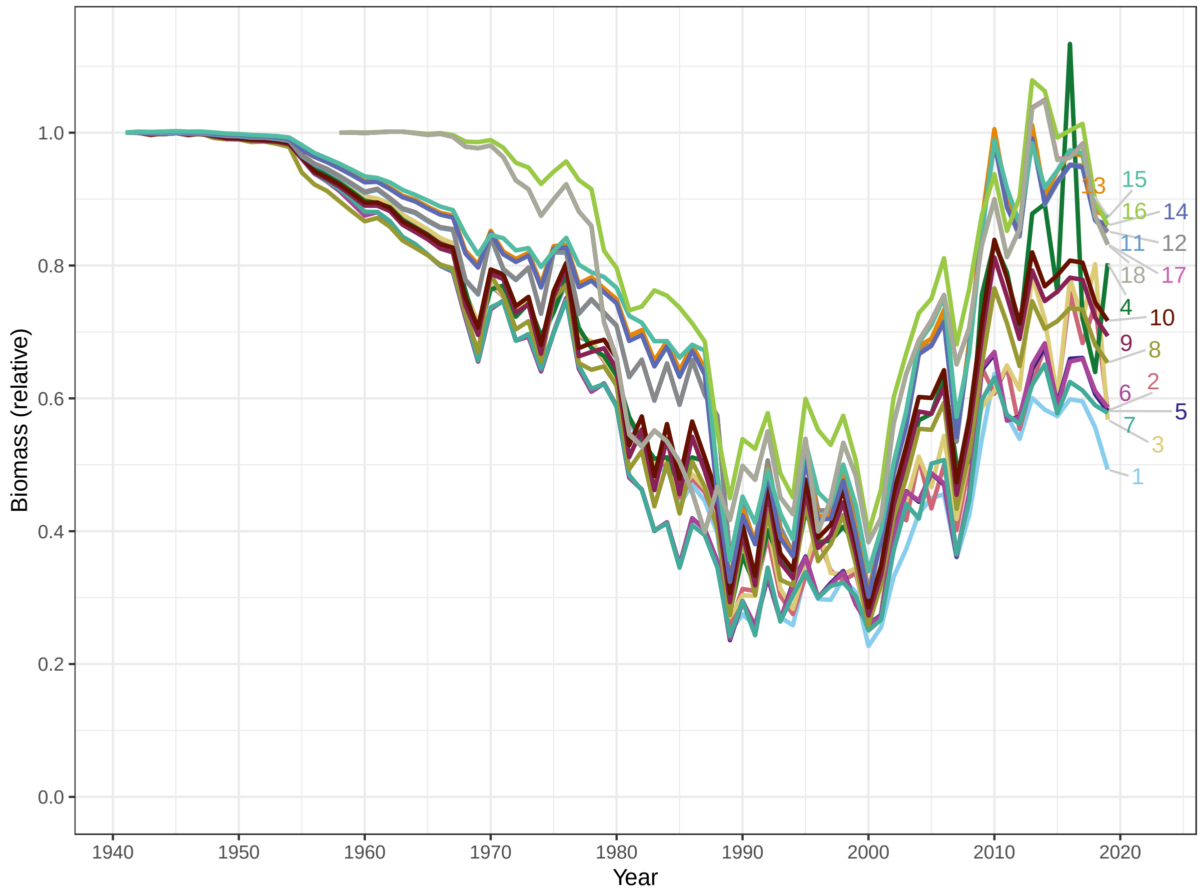


Figure E.1: Biomass ratio (relative to unfished) bridging scenarios for tiger prawns, scenarios are 1) original 2021 model (northern region), 2) extended fitting routine, 3) increase σ_R upper bound to 0.5, 4) change steepness prior, 5) add seasonal q, 6) add a prior for μ, 7) add a prior for k, 8) change the recruitment function, 9) remove the penalty for if the catch is greater than the recruits, 10) new data for weight at recruitment, 11) recalculate ρ, 12) change survivorship function, 13) start recruitment deviations from 1988, 14) new equations for cpue and recruitment deviations log likelihood, 15) change to DDUST model, 16) change to data input for this assessment (truncated to 2019), 17) change to REDDUST model, 18) project team preferred model inputs for this assessment (truncated to 2019)

Appendix F Delay-Difference with User Specified Timestep (DDUST)

The following delay-difference modelling framework is based on the models developed in several previous reports, including O'Neill et al. (2005), O'Neill et al. (2006b), Courtney et al. (2014a), O'Neill et al. (2014), and Helidoniotis (2021). Functionality has been introduced to allow the user to specify the time step used for delays and incorporate seasonal variation in recruitment, spawning, and catchability. The delay-difference with user specified time step (DDUST) and random effect delay-difference with user specified time step (REDDUST) models allow for monthly, bimonthly, trimonthly, quadmonthly, semi-annual and annual biomass dynamics. REDDUST extends DDUST by treating annual recruitment variations as random effects.

F.1 Mathematical formulation

F.1.1 Population dynamics

The delay-difference model stages the population into recruits and spawners. The spawning biomass, B, represents the total biomass of the fishery contributing to spawning and the recruits, R, represents the quantity of spawners that are recruited to the fishery, i.e., become available for fishing. The population dynamics are governed by the delay-difference model, equation 5.15 of Quinn II et al. (2000),

$$B_t = (1+\rho)s_{t-1}B_{t-1} - \rho s_{t-1}s_{t-2}B_{t-2} - \rho s_{t-1}w_{r-1}R_{t-1} + w_r R_t, \tag{F.1}$$

$$N_t = N_{t-1}s_{t-1} + R_t. \tag{F.2}$$

The spawning biomass at time t depends on the spawning biomass in the two previous time steps. The growth of the population is controlled through the parameter ρ and the total mortality (natural and fishing) is represented by s. The first term in equation (F.1) can be interpreted as the growth of surviving adults and the second term as a dampening of the otherwise exponential growth. The third and fourth terms represent the addition of recruits. The number of individuals is easier to track but often less important. Without the need to track growth or weight, equation (F.2) describes individuals experiencing mortality and the addition of recruits. A key feature of the REDDUST package is that the user can specify how fine the timescale is for the above equations. In an annual model, the biomass in year t is dependent on the biomass in the two previous years. In the monthly model, the biomass in month t is dependent on the biomass in the previous two months. This pattern extends to the bimonthly, trimonthly, quadmonthly, and semi-annual models.

F.1.2 Recruitment

Independent of the model type, the recruitment is calculated from the spawning biomass from the previous year using the Beverton-Holt equation and distributed according to the recruitment pattern ϕ,

$$R_t = \phi_{\mathrm{mod}(t,dt)} \frac{\sum_{t'} SB_{t'}}{\alpha + \beta \sum_{t'} SB_{t'}} \tag{F.3}$$

where $t' = \{t-N_m, t-N_m+1, \ldots, t-1\}$. This means that the spawning biomass of the previous 12 months, regardless of the model timestep, is summed to inform recruitment. Annual recruitment is primarily dependent on the spawning biomass but unmeasured random processes may cause the recruitment to deviate from the strict relationship imposed by the Beverton-Holt equation (F.3). In the frequentist paradigm, which has been traditionally used in stock assessments, the recruitment deviations are included through a penalised likelihood. Maunder et al. (2003) shows, however, that the variance σ_R^2 of the deviations cannot be estimated using this approach. It is best to integrate out the recruitment deviations (leaving a marginal likelihood) or implement a state-space model (Punt 2023) - both of these approaches treat recruitment deviations as random effects. Deviations from the annual recruitment R_t are treated as fixed effects in DDUST and random effects in REDDUST by integrating the recruitment parameters out of the likelihood. In REDDUST, the relationship between the annual recruitment R_t and the deviated recruitment R_t^* is as follows,

$$R_t^* = R_t e^{\eta_t - b_t \sigma_R^2/2}, \qquad e^{\eta_t} \sim \text{Lognormal}(0, \sigma_r^2). \tag{F.4}$$

The subtraction of $\sigma_R^2/2$ ensures the mean of R_t^* is equal to the mean of R_t and the bias correction b_t is a bias correction to downplay recruitment deviations informed by little data. The calculation of b_t is described in Methot et al. (2011). In the current applications of DDUST and REDDUST, all time steps equally have one catch rate data point and one catch data point so b_t has been omitted. In order to produce useful model diagnostics, the recruitment deviation is calculated within the model as the difference between the logarithms of the parameter vector R_t^* and the recruitment R_t,

$$\eta_t = \log(R_t^*) - \log(R_t) - \sigma_R^2/2. \tag{F.5}$$

A plot of the time series of recruitment deviations can reveal patterns or unusually high or low recruitment spikes which may require external justification. Since the models do not use data that can truly inform recruitment, the recruitment deviations will often show the trend set out by the catch rate data. It is up to the analyst on how to treat this limitation. Equation (F.1) and (F.2) are updated using the recruitment deviations described in equation (F.4)

$$B_t^* = (1+\rho)s_{t-1}B_{t-1}^* - \rho s_{t-1}s_{t-2}B_{t-2}^* - \rho s_{t-1}w_{r-1}R_{t-1}^* + w_r R_t^*, \tag{F.6}$$

$$N_t^* = N_{t-1}^* s_{t-1} + R_t^*. \tag{F.7}$$

From now on, B_t^*, N_t^* and B_t, N_t are used interchangeably.

F.1.3 Spawning

The recruitment derived in equation (F.3) depends on the total annual female spawning biomass after exposure to natural and fishing mortality. With the assumption of a 50/50 sex ratio and distribution of spawners throughout the year according to P_i, the spawning biomass is given by

$$SB_t = \frac{P_i}{2}\left(\frac{1-s_t}{-\log(s_t)}\right)N_t \tag{F.8}$$

where $i = \text{mod}(t, N_m) = t \mod N_m$. N_m is the number of timesteps in a year (i.e. for a monthly model, N_m is 12 so i is an integer between 1 and 12 inclusive and P_i is the proportion of spawners allocated to each month). The term $\frac{1-s_t}{-\log(s_t)}$ is an adjustment of the survivorship such that SB_t is the spawning biomass in the middle of the time step. The survivorship is the product of natural mortality, $s = \exp\left(-M \cdot \frac{N_m}{12}\right)$, and fishing mortality, calculated by comparing the catch data and biomass trajectory,

$$s_t = s\left(1 - \min\left(\frac{C_t}{B_t}, 0.99\right)\right). \tag{F.9}$$

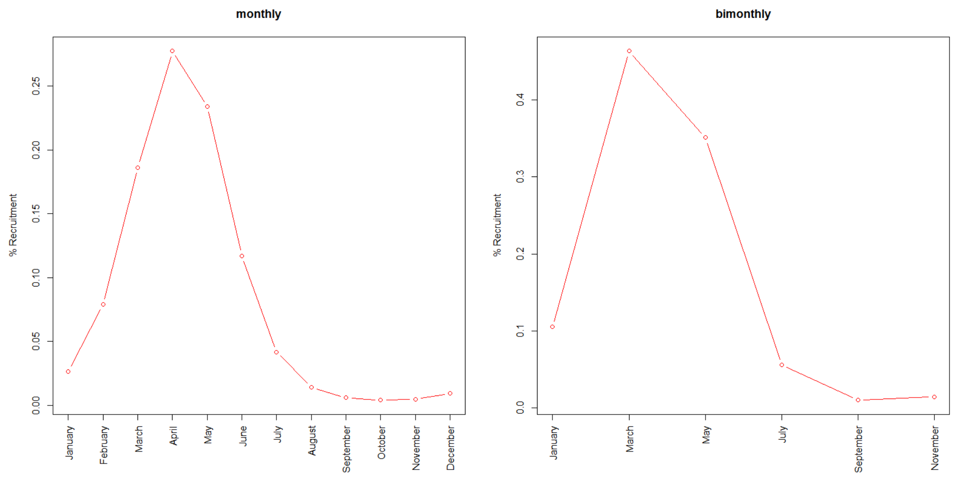


Figure F.1: Aggregation of a monthly recruitment pattern for a bi-monthly model

In order to maintain a differentiable objective function, the smoothed approximation of the $\min$ function is used:

$$\min(\theta_1, \theta_2) = \frac{1}{2}(\theta_1 + \theta_2) - \sqrt{\frac{1}{4}(\theta_1 - \theta_2)^2 + 4\delta\theta_2}. \tag{F.10}$$

The recommended value for δ is $\frac{1}{1000}$.

F.1.4 Seasonal patterns

The REDDUST package has the capacity for intra-annual patterns of spawning and recruitment. The spawning pattern indicates the proportion of the adult female population spawning during each month and must be specified by the user. The recruitment pattern indicates how the recruits are distributed among the year and is governed by two parameters κ and μ which can be fixed or estimated by the model. The monthly recruitment pattern is assumed to follow an exponential cosine function

$$\phi_t = \frac{\exp\left(\kappa \cos(t-\mu)\frac{2\pi}{12}\right)}{\sum_{t'=1}^{12} \exp\left(\kappa \cos(t'-\mu)\frac{2\pi}{12}\right)}, \qquad t \in \{1, \ldots, 12\}. \tag{F.11}$$

Due to the cyclic nature of the cosine function, the parameters κ and μ may produce the exact same pattern at different fixed values. Both the spawning pattern and recruitment pattern are converted to the appropriate time step by summing the proportions in adjacent months. For example, in the bimonthly model, the recruitment in January and February is combined and attributed to January. The recruitment in March and April is combined and attributed to March and so on. Figure F.1 shows how the monthly pattern is aggregated for a bimonthly model. The proportion spawning in each month is converted in the same way. This process results in recruitment and spawning vectors with length $dt = \frac{12}{N_m}$ which are invariant to year.

F.1.5 Growth

Growth is most commonly modelled using the von Bertalanffy model relating length to age

$$L(a) = L_\infty \left[1 - e^{-\kappa(a-t_0)}\right] \tag{F.12}$$

developed by von Bertalanffy (1938). For use in the delay-difference model, equation F.12 is re-parameterised in terms of the Brody growth coefficient ρ and weight of recruits w_r and pre-recruits w_{r-1}

$$L_\infty = \frac{w_r - \rho w_{r-1}}{1-\rho} \tag{F.13}$$

$$\kappa = -\ln(\rho) \tag{F.14}$$

$$t_0 = r - 1 - \frac{1}{\ln(\rho)} \ln\left(\frac{w_r - w_{r-1}}{w_r - \rho w_{r-1}}\right). \tag{F.15}$$

The above substitutions result in the weight-at-age form which describes growth of individuals older than recruitment age, $a > r$,

$$W(a) = w_{r-1} + (w_r - w_{r-1})\frac{1-\rho^{1+a-r}}{1-\rho}. \tag{F.16}$$

Asymptotic weight from equation (F.16) is then

$$W_\infty = \underset{a\to\infty}{W(a)} = w_{r-1} + \frac{w_r - w_{r-1}}{1-\rho}. \tag{F.17}$$

This method is set out in Quinn II et al. (2000). The growth parameter ρ can therefore be calculated using knowledge of weight at recruitment, weight pre-recruitment and asymptotic weight:

$$\rho = 1 - \frac{w_r - w_{r-1}}{w_\infty - w_{r-1}}. \tag{F.18}$$

In REDDUST, the growth parameter ρ is calculated using equation (F.18) if $y_\rho = 1$, otherwise it is the value provided in the data object.

F.1.6 Stock-recruitment parameters

Dichmont et al. (2003) recommends that 'spawning stock size and recruitment are estimated separately from the parameters of the stock–recruitment relationship... to avoid assumptions about the form of the stock–recruitment relationship and the extent of variation and inter-annual correlation in the residuals about that relationship impacting the estimates of spawning stock size and recruitment.' In REDDUST, recruitment parameters for the stock-recruitment relationship are derived from the equilibrium outputs. The unfished equilibrium biomass is derived numerically by simulating the population dynamics for N_e years. Although there exist closed form solutions in the case of annual time steps (Hilborn et al. 1992a), all models use numerical simulation for consistency. Given fixed annual recruitment, the population dynamics are described by

$$\overline{B}_t = (1+\rho)s\overline{B} - \rho s^2\overline{B} - \rho s w_{r-1} R_{t-1} + w_r R_t \tag{F.19}$$

$$\overline{N}_t = s\overline{N} + R_t \tag{F.20}$$

with initial recruitment and survivorship computed from the parameter R_{init}

$$R_0 = \exp(R_{\text{init}}) \cdot R_{\text{scalar}}, \tag{F.21}$$

$$R_t = R_0 \cdot \phi_{\text{mod}(t,dt)}, \tag{F.22}$$

$$s = \exp\left(-\frac{M}{dt}\right). \tag{F.23}$$

The equilibrium outputs are found when $|N_t - N_{t+1}| < \epsilon$ for some appropriately small $\epsilon > 0$. REDDUST relies on the assumption that this occurs after N_e years of iterations. Users should validate this assumption with a convergence test. The outputs are then relabelled as

$$\overline{N} = N_t = N_{t-1} \tag{F.24}$$
$$\overline{B} = B_t = B_{t-1}. \tag{F.25}$$

Equilibrium spawning biomass is calculated as

$$\overline{SB} = \frac{1}{2}\left(\frac{1-s}{-\log(s)}\right)\overline{N} \tag{F.26}$$

In words, the equilibrium spawning stock SB^* is the female portion (assumed to be 50%) of the surviving equilibrium stock after exposure to natural mortality. The stock-recruitment parameters to be used in equation F.3 are then

$$\alpha = \frac{\overline{SB}(1-h)}{4hR_0}, \tag{F.27}$$
$$\beta = \frac{5h-1}{4hR_0} \tag{F.28}$$

where $h = \dfrac{1+\exp(\xi)}{5+\exp(\xi)}$. This parameterisation of the stock-recruitment relationship assumes that the equilibrium population has attained a stable age distribution (Haddon 2001).

F.1.7 Abundance indices

The DDUST and REDDUST models fit to one or more time series of abundance indices. The model assumes the following relationship between catch and abundance,

$$C_t = qE_tB_t \tag{F.29}$$

where q is the catchability coefficient and E is fishing effort. Multiple time series, indexed by f may be used to model different catchabilities between fleets, areas or before and after management changes. The predicted catch per unit effort (abundance index) is calculated from the biomass, using q to scale,

$$\hat{I}_{f,t} = \frac{C_{f,t}}{E_{f,t}} = q_f B_t. \tag{F.30}$$

In addition to fleet-specific catchability, the model allows the catchability coefficient to vary within the year (seasonal q). It does this by first comparing the abundance index data to the biomass at the mid-point of each timestep,

$$log(q_{\text{base}}) = \log\left(\frac{I_t}{B_t\frac{1-s_t}{-log(s_t)}}\right). \tag{F.31}$$

The parameters q_1 and q_2 control the pattern of catchability over the seasons according to the form

$$q_t = \exp\left(log(q_{\text{base}}) + q_1\cos\left(\frac{2\pi t}{12}\right) + q_2\sin\left(\frac{2\pi t}{12}\right)\right). \tag{F.32}$$

The above equation is a modified version of the equation published in Courtney et al. (2014a) with $q_1 = q_{\text{peak}}$ and $q_2 = q_{\text{peak}} \cdot q_{\text{amp}}$,

$$q_t = \exp\left(log(q_{\text{base}}) + q_{\text{amp}}\left(\cos\left(\frac{2\pi t}{12}\right) + q_{\text{peak}}\sin\left(\frac{2\pi t}{12}\right)\right)\right). \tag{F.33}$$

The predicted abundance index is therefore

$$\hat{I} = -q_t B^*_t \frac{1 - s_t}{log(s_t)}, \tag{F.34}$$

recalling that $-\frac{1-s_t}{log(s_t)}$ shifts the calculation to represent the middle point of the timestep.

F.2 Likelihood components

The likelihood has four main components: abundance indices log-likelihood, recruitment deviation log-likelihood, penalties and priors. The abundance indices log-likelihood is

$$LL_I = \frac{\log(\sigma_I)}{2} + \sum_t \left[\frac{\left(\log(\hat{I}_t) - \log(I_t)\right)^2}{2\sigma_I}\right]. \tag{F.35}$$

The recruitment deviation log-likelihood in REDDUST is

$$LL_R = \frac{\log(\sigma_R)}{2} + \sum_t \left[\frac{\left(\log(R^*_t) - \log(R_t)\right)^2}{2\sigma_R}\right]. \tag{F.36}$$

The recruitment deviation log-likelihood in DDUST is

$$LL_R = \frac{\log(\sigma_R)}{2} + \sum_t \left[\frac{\zeta_t^2}{2\sigma_R}\right]. \tag{F.37}$$

There are two penalties implemented in the likelihood. The catch penalty prevents the catch from exceeding the exploitable biomass

$$P_{\text{catch}} = \frac{1}{2}\sum_t \left[\frac{\left(\log(\frac{C_t}{1000}) - \log(\frac{B_t}{1000})\right)^2}{2\sigma_1}\right]. \tag{F.38}$$

The recruitment penalty prevents the model from estimating a unrealistically high value of R_{init} by penalising the model if the catch is less than 5% of the recruits

Priors are used to assist in convergence of the optimising algorithm. A prior for steepness is imposed on the transformed parameter ξ using a log-normal distribution. In Figure F.2a the prior on the transformed parameter ξ is

$$\xi \sim \text{Log-normal}(\mu_\xi = \log(3), \sigma^2_\xi = 1). \tag{F.39}$$

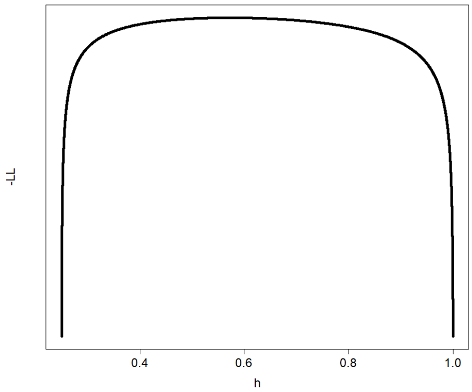
Figure F.2b shows that in the original h space, this prior is actually quite uniform, only having an effect if h is close to 0.2 or 1. The prior contributions to the log-likelihood are

$$P_\xi = \frac{1}{2}\frac{(\xi - \mu_\xi)^2}{\sigma^2_\xi}, \tag{F.40}$$

$$P_\mu = \frac{1}{2}\frac{(\mu - \mu_\mu)^2}{\sigma^2_\mu}, \tag{F.41}$$

$$P_\kappa = \frac{1}{2}\frac{(\kappa - \mu_\kappa)^2}{\sigma^2_\kappa}. \tag{F.42}$$

(a) log-normal prior of transformed parameter ξ



(b) transformed prior of original parameter h

Figure F.2: Transformation of the prior on steepness parameter ξ

The total log-likelihood is the sum of the above contributions

$$LL = LL_I + LL_R + P_{\text{catch}} + P_{\text{recruits}} + P_\xi + P_\mu + P_\kappa. \tag{F.43}$$

Appendix G Stock Synthesis

G.1 Introduction

Demographic analyses such as fishery stock assessments are used to determine the effect of fishing upon a given fish stock (Methot et al. 2013). One such demographic analysis is the statistical age-structured population modelling framework 'Stock Synthesis.' Stock synthesis uses an integrated analysis approach whereby several sources of data can be combined into a single model through a joint likelihood for observed data (Carvalho et al. 2021).

Previously, fishery assessments were tailored to each specific fishery using bespoke models written by the user (Dichmont et al. 2021). More recently, software packages such as Stock Synthesis which implement assessment methods have gained popularity (Dichmont et al. 2016b). Assessment packages are designed to allow the user to apply established analyses to their own data removing the need to code bespoke models (Dichmont et al. 2021). The use of assessment packages where appropriate limits redundancy, decreases the time and cost required, and removes the potential for programming errors when compared to implementing bespoke models (Dichmont et al. 2021; Wilson et al. 2014). Dichmont et al. (2016a) noted benefits such as: (a) increased flexibility enabling diverse assessment design, (b) easier peer-review, (c) decreased instances of incorrect coding, (d) increased collaboration among scientists when using common software, (e) decreased assessment duration, (f) capability of new scientists to take over an assessment given common software, (g) tools available to investigate model uncertainty and interpret model fits, and (h) further development and improvement can be facilitated through a large user base.

Age-based demographics are integral to the life history and biology of fished species. Characteristics such as longevity, growth rates, mortality estimates and age at maturity underpin population dynamics and therefore, are critical to stock assessment (Campana 2001). For teleosts, age data can be obtained through the examination of growth bands composed within hard structures (i.e., primarily otoliths but also bones, scales and vertebrae). Obtaining age data from crustaceans such as crabs, prawns, and bugs has proven challenging given crustaceans must moult to grow (Hartnoll 1978; Hartnoll 2001).

Most stocks that have been assessed using Stock Synthesis have been teleosts or elasmobranchs (Methot et al. 2013). Stock Synthesis is well suited to teleosts where the estimation of age data through otoliths is well understood, allowing the model to calculate numbers in each age class in each year. Few stock assessments have used Stock Synthesis to determine stock status for crustaceans (but see Bergenius et al. 2016; Hart 2015; Hart 2018). Two main reasons likely explain why few crustaceans have been assessed with an age-based analysis such as Stock Synthesis. Firstly, a lack of direct age data or growth data to calculate numbers in each age class in each year. Secondly, given the short life span of crustaceans and calculations based on numbers in each year class, an annual model time step may not sufficiently capture the biology of crustaceans (e.g. multiple spawning and recruitment events per year). Stock Synthesis contains methods to attempt to overcome both of these challenges. Provided length frequency and growth curve information are available for the species assessed, a growth curve provides a means of converting length to an approximate age. Stock Synthesis can also be configured to run on a monthly time step (e.g. allowing recruitment to be distributed throughout months rather than a single pulse recruitment in a single month).

This appended assessment aims to explore the use of an age-based analysis (Stock Synthesis) on east coast tiger prawns. In doing so, this assessment also aims to estimate the current biomass for the Queensland east coast tiger prawn population using a monthly time step Stock Synthesis model.

G.2 Methods

G.2.1 Data

The methods used to develop the retained catch and standardised index inputs were the same as those used in the project team preferred delay-difference model (described in Sections 3.1.2 and 3.1.3).

Length data from the Fisheries Queensland biological monitoring program (Fisheries Queensland 2012a) were input to the population model in one-millimeter length bins.

G.2.2 Population model

A population model with monthly time steps was fitted to the data to determine the number of tiger prawns in each year and each age group using the software package Stock Synthesis (SS; version 3.30.20). A full technical description of SS is given in Methot et al. (2021).

The model used one fleet for the project team preferred scenario, representing the entire fishery. For scenario 2, the model was split into three fleets, split temporally to represent the introduction of fishery area closures: fleet one represents the fishery before 1986, fleet two represents the fishery from 1986 to 2004, and fleet three represents the fishery since 2004.

Given the limited sex-specific length data available, the population model was run as a one-sex model.

G.2.3 Model assumptions

The main assumptions underlying the model are given below:

- The fishery began from an unfished state in 1958.
- Prawns swim freely and mix rapidly within the bounds of each stock, so that the different fleets compete for the same prawns rather than targeting different sub-populations.
- Genetic stocks along Queensland's east coast are reproductively isolated from one another.
- The proportion of mature prawns depends on size and not age.
- The proportion of mature prawns vulnerable to fishing depends on size and not age.
- Growth occurs according to the von Bertalanffy growth curve.
- The instantaneous natural mortality rate does not depend on size, age, year or sex.
- Deterministic annual recruitment is a Beverton-Holt function of stock size.

G.2.4 Model parameters

A variety of parameters were included in the model, with some of these fixed at specified values and others estimated, and known as *uniform priors*. Uniform priors were used unless stated otherwise.

The natural logarithm of unfished recruitment (SR_LN(R0)) was estimated within the model.

Recruitment was calculated once per year and an apportionment of this recruitment to each month was estimated within the model.

Beverton-Holt stock recruitment steepness (SR_BH_steep) was estimated within the model with a prior. Steepness is a metric relating to the productivity of the stock. Specifically, steepness refers to the fraction of recruitment from a virgin population that is obtained when the population is at 20% of virgin biomass (Lee et al. 2012).

As age data were unavailable, parameters of the von Bertalanffy growth curve (L_at_Amin, L_at_Amax, VonBert_K) were fixed, as well as the coefficient of variation for young prawns (CV_young). The coefficient of variable of old prawns (CV_old) was estimated within the model.

The Stock Synthesis growth curve was defined by brown tiger prawn growth only, whereas the growth curve used in the delay-difference models were informed by both brown and grooved tiger prawns (Section 2.4.4).

Natural mortality was fixed in the model at 0.18 per month.

Logistic length-based selectivity parameters were estimated in the model without priors (Size_inflection, Size_95%width). In scenario two, separate selectivity curves were estimated for each fleet (time period).

Recruitment deviations between 1988 and 2021 improved fits to composition data and abundance indices as variability in recruitment annually allowed for changes in the population on shorter time-scales than fishing mortality alone.

G.2.5 Model weightings

A Francis adjustment (Francis 2011) was applied to all the length compositions fits, to attempt to achieve a suitable effective sample size (and thus relative weighting).

G.2.6 Sensitivity tests

A subset of the sensitivity tests used in the project team preferred (delay-difference) modelling framework were tested using Stock Synthesis, described in Table G.1. These correspond to Scenarios 1 to 3, in which the project team preferred settings were used for each scenario except three treatments to catch rates were used, as well as scenarios to test the scaling up and down of historical retained catch data. The recruitment deviations were estimated as parameters starting in 1988 and voluntary catch rate (HTRAWL) data were included.

Table G.1: Scenarios tested to determine sensitivity to parameters, assumptions and model inputs for east coast tiger prawns using Stock Synthesis

Scenario	Catch rates	Historical retained catch data
1 (Base)	Continuous	150%
2	Offset	150%
3	Split	150%
4	Continuous	100%
5	Continuous	200%

G.3 Results

G.3.1 Model inputs

G.3.1.1 Data availablity

Figure G.1 summarises the assembled data sets input to the Stock Synthesis model.

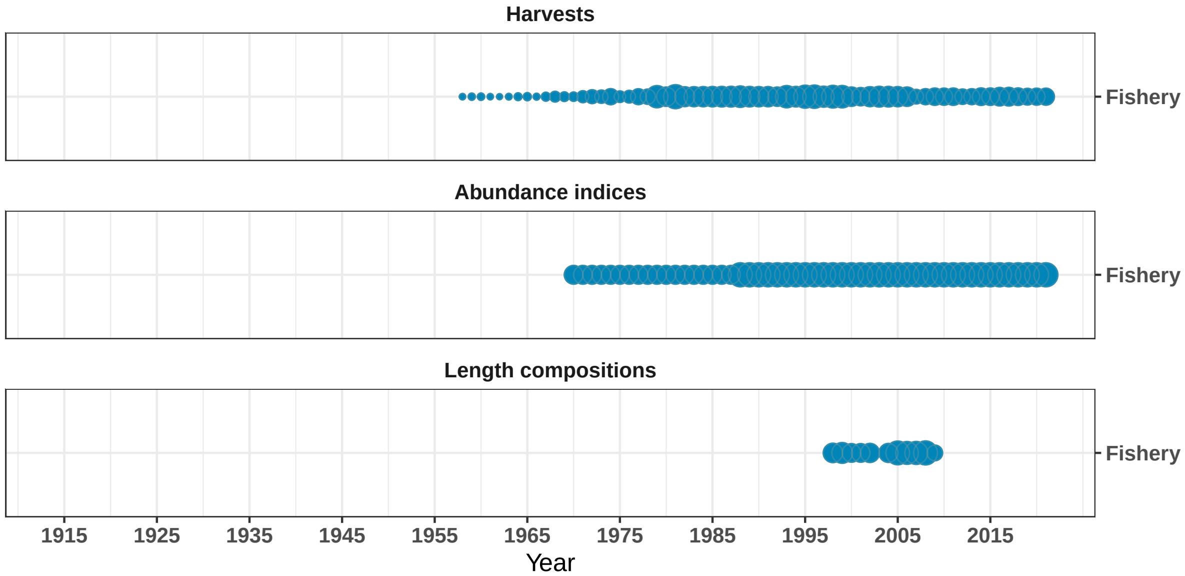


Figure G.1: Data presence by year for each category of data type used in the Stock Synthesis model

Note: Stock Synthesis uses the term 'fleet' to distinguish data sets (and model processes) associated with different selectivity curves (proportions of fish at different lengths vulnerable to the fishing gear). The project team preferred scenario for the Stock Synthesis scenario of this assessment involves one fleet. This plot shows data presence by year for this fleet, where circle area is relative within a data type. Circle areas are proportional to total catch for catches; to precision for indices and discards; and to total sample size per fleet for compositions. Note that since the circles are scaled relative to maximums within each data type, the scaling between separate data types should not be compared.

G.3.2 Length composition

Prawn length compositions were input to the Stock Synthesis population model (Figure G.2).

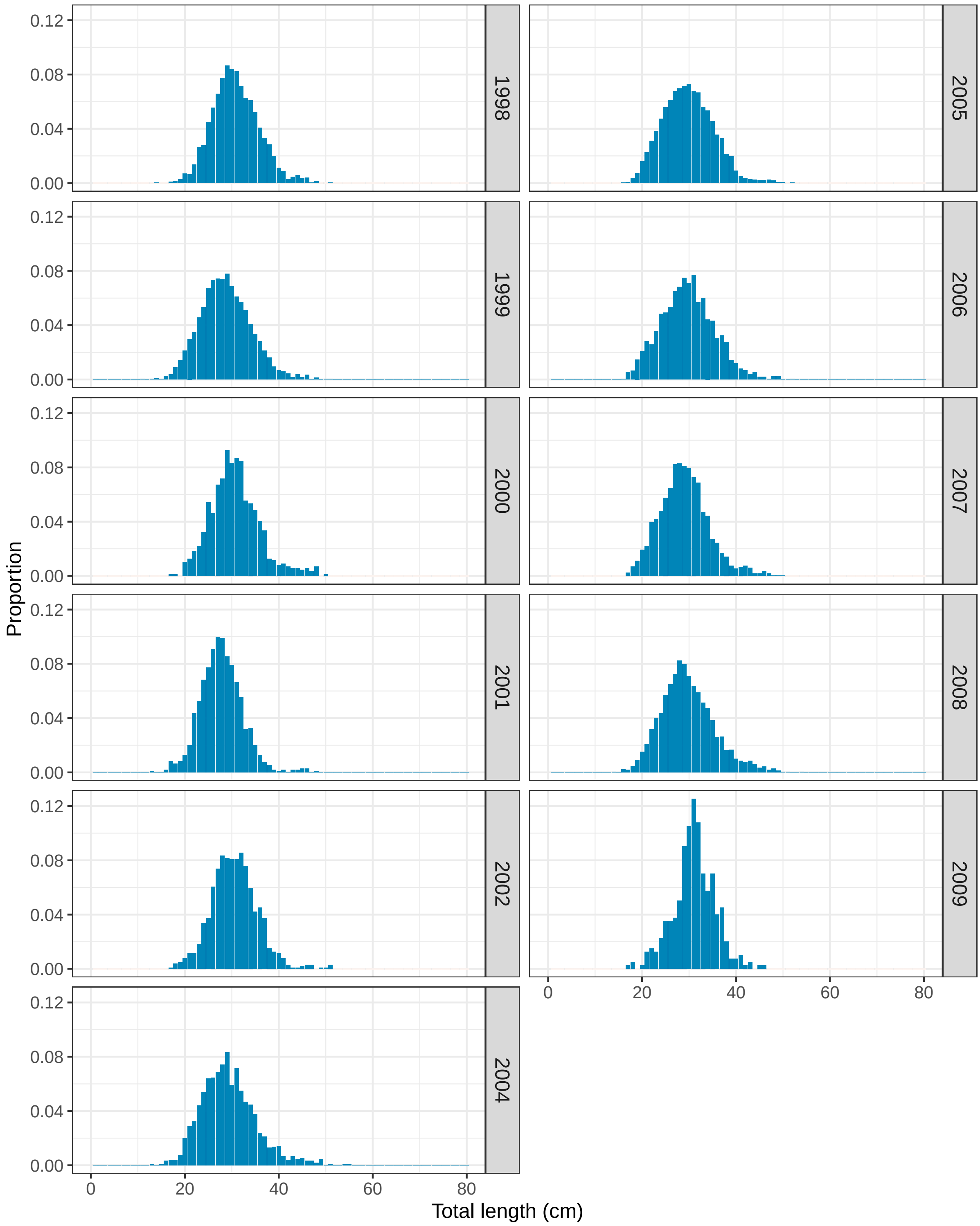


Figure G.2: Annual length compositions of tiger prawns for commercially harvested prawns between 1998 and 2009

G.3.3 Model outputs

G.3.3.1 Model parameters

A number of parameters were estimated within the Stock Synthesis model (Table G.2).

Table G.2: Summary of parameter estimates from the Stock Synthesis population model

Parameter	Estimate	Standard deviation	Phase	Min	Max	Initial value
Beverton-Holt steepness parameter	0.67	0.01	6	0.2	1	0.6
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1958)	12.78	0.02	1	3	30	20
Coefficient of variation in length at maximum age	0.18	0.01	5	0.01	0.5	0.3
Commercial selectivity inflection (cm)	2.63	0.02	2	0.05	3	2.1
Commercial selectivity width (cm)	0.56	0.03	3	0.1	5	0.52
Recruitment distribution parameter for month 10 (October) in logit space	1.86	715157	3	-80	80	0
Recruitment distribution parameter for month 11 (November) in logit space	52.25	2463.78	3	-80	80	0
Recruitment distribution parameter for month 12 (December) in logit space	-61.55	292045	3	-80	80	0
Recruitment distribution parameter for month 2 (February) in logit space	8.22	707990	3	-80	80	0
Recruitment distribution parameter for month 3 (March) in logit space	-69.91	169118	3	-80	80	0
Recruitment distribution parameter for month 4 (April) in logit space	28.32	316407	3	-80	80	0
Recruitment distribution parameter for month 5 (May) in logit space	50.97	2463.78	3	-80	80	0
Recruitment distribution parameter for month 6 (June) in logit space	49.66	2463.78	3	-80	80	0
Recruitment distribution parameter for month 7 (July) in logit space	13.77	694019	3	-80	80	0
Recruitment distribution parameter for month 8 (August) in logit space	12.82	696872	3	-80	80	0
Recruitment distribution parameter for month 9 (September) in logit space	-78.63	24226.9	3	-80	80	0

Most model scenarios had parameters that were estimated cleanly (none hit their bounds), and final parameter gradients were small, implying no convergence problems.

G.3.3.2 Model fits

Abundance indices

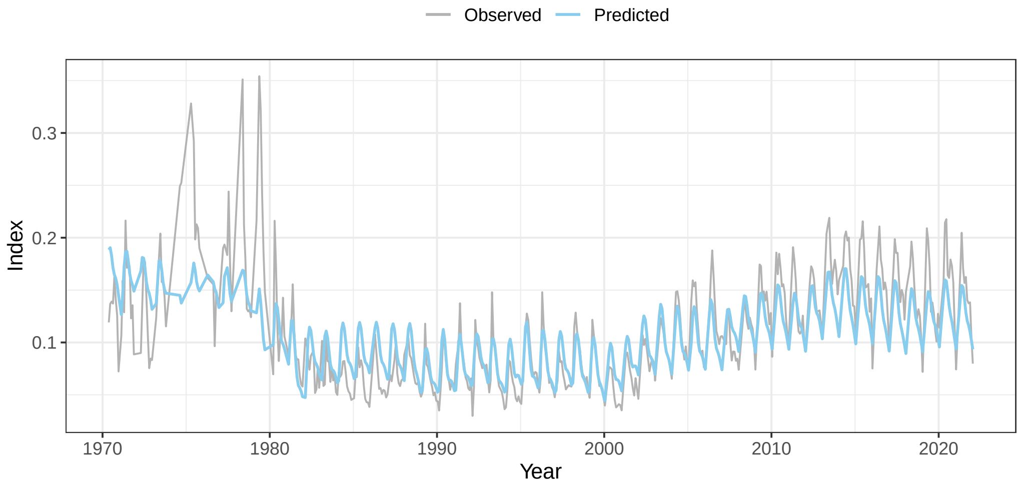


Figure G.3: Model predictions (blue line) to catch rates for east coast tiger prawns

Length compositions

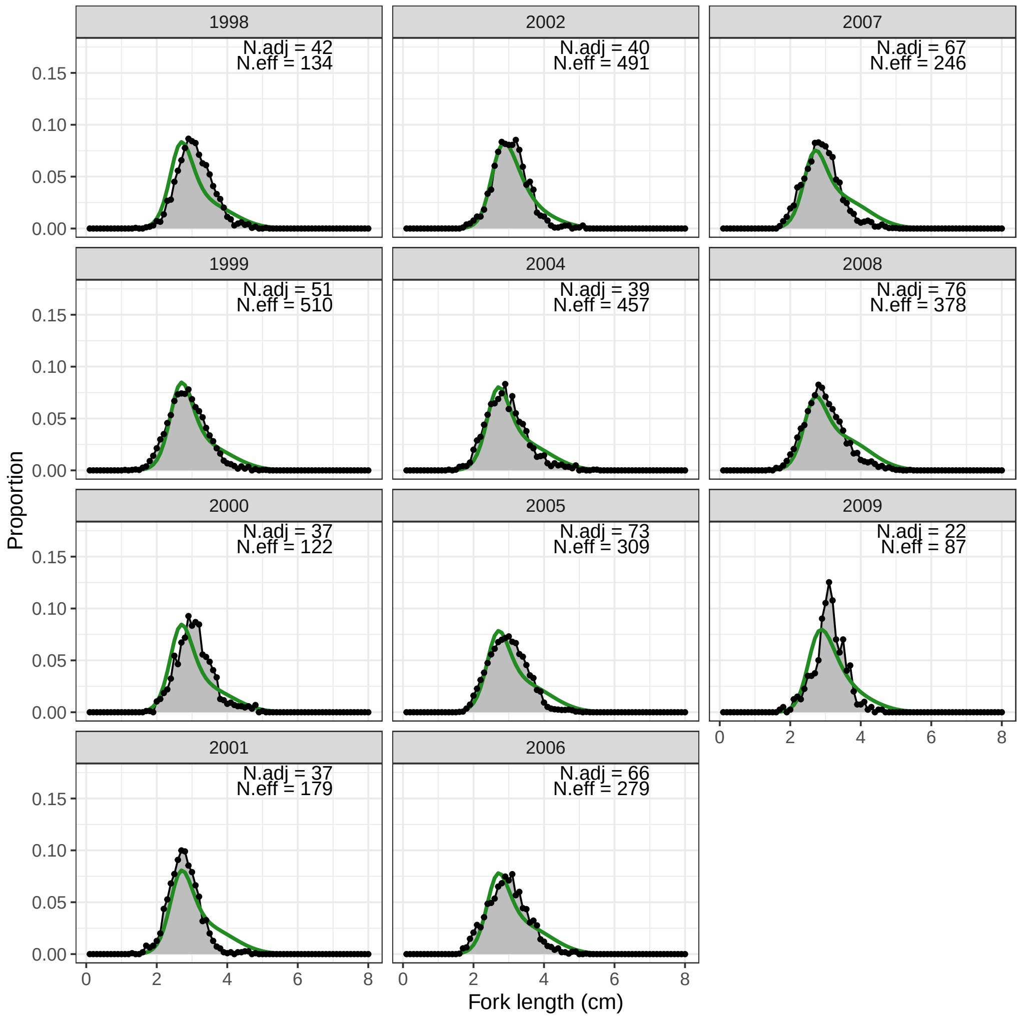


Figure G.4: Length structure for the commercially harvested east coast tiger prawns

G.3.3.3 Selectivity

Selectivity of tiger prawns was estimated within the model.

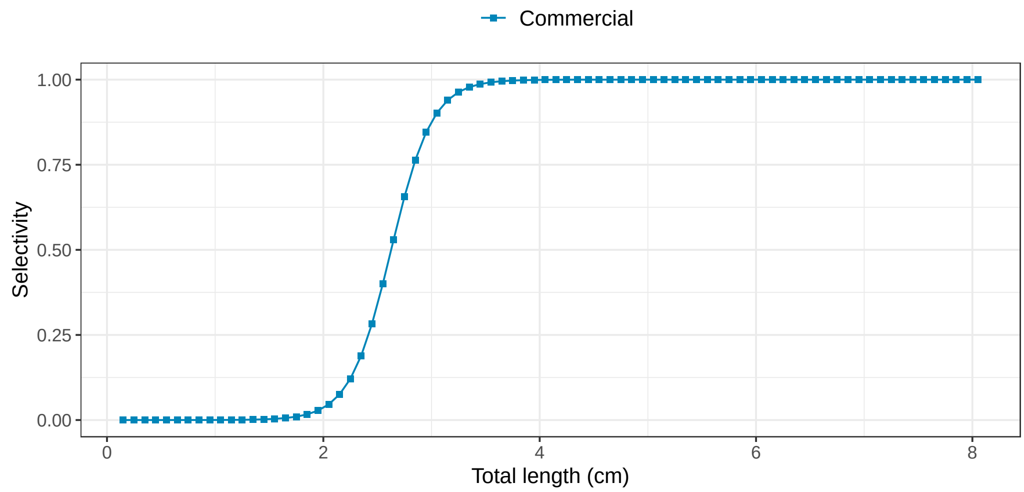


Figure G.5: Model estimated length-based selectivity for east coast tiger prawns

G.3.3.4 Growth curve

The von Bertalanffy growth curve was fixed within the model, however the coefficient of variation of old prawns was estimated within the model (Table G.2, Figure G.6).

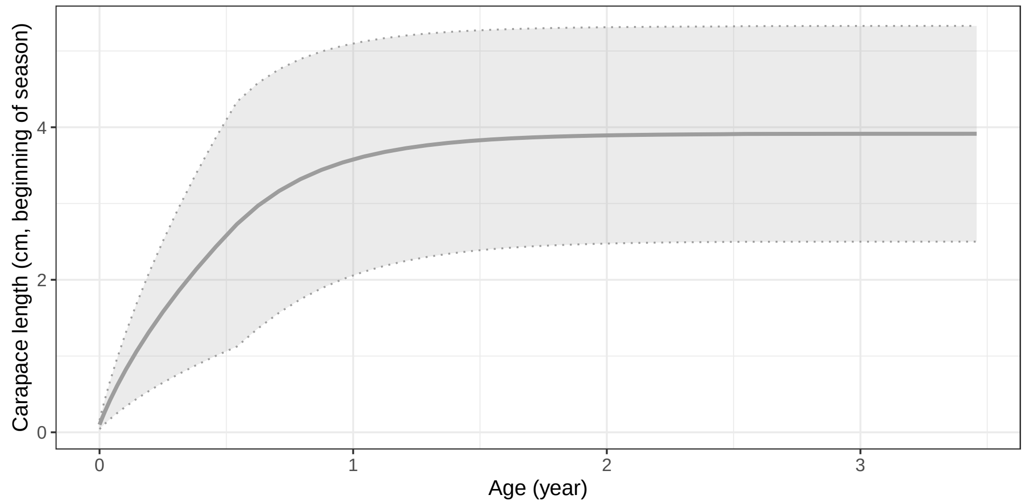


Figure G.6: Model estimated growth of tiger prawns on the east coast of Queensland (shading represents 95% confidence intervals)

G.3.3.5 Recruitment distribution

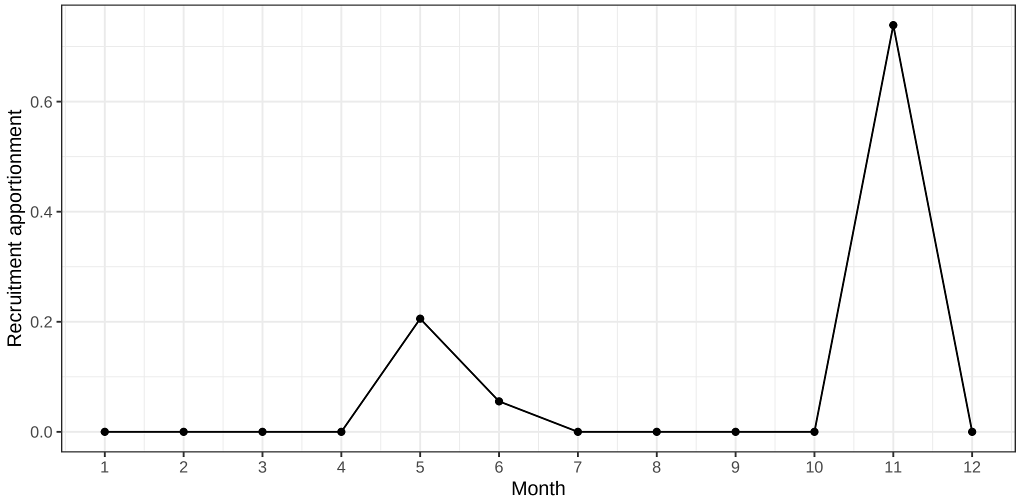


Figure G.7: Recruitment deviations with 95% confidence intervals for east coast tiger prawns

G.3.3.6 Biomass

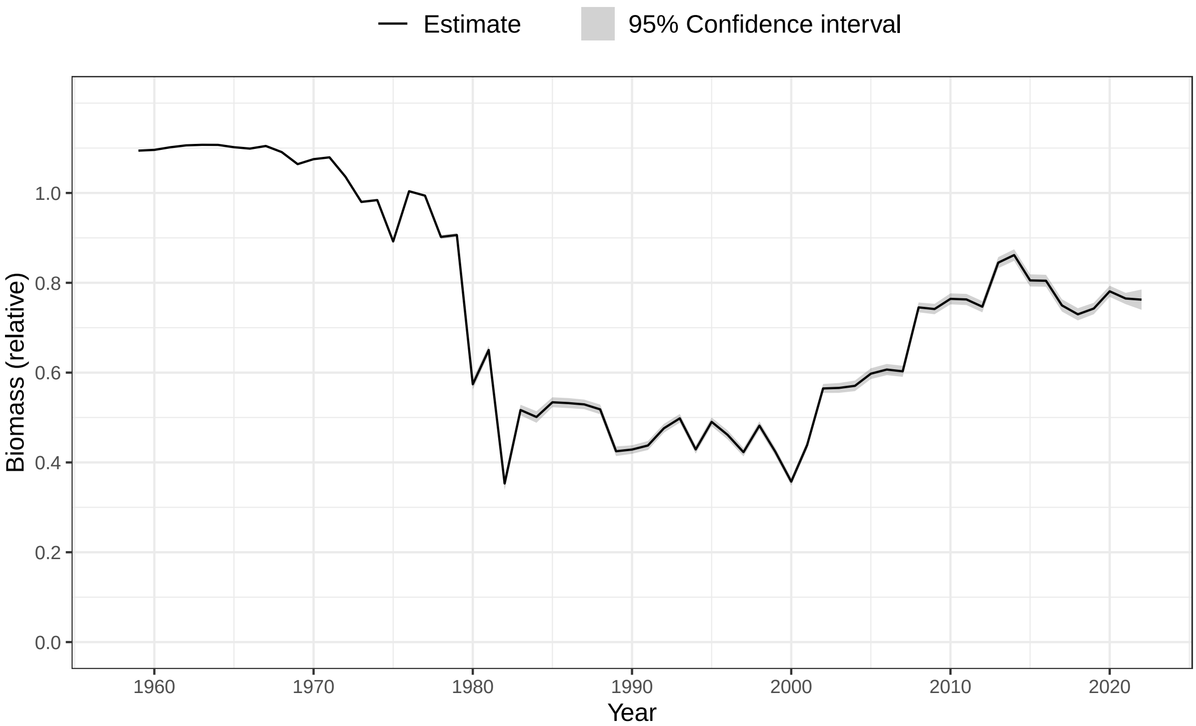


Figure G.8: Predicted stock biomass trajectory relative to unfished, from 1958 to 2021 for east coast tiger prawns

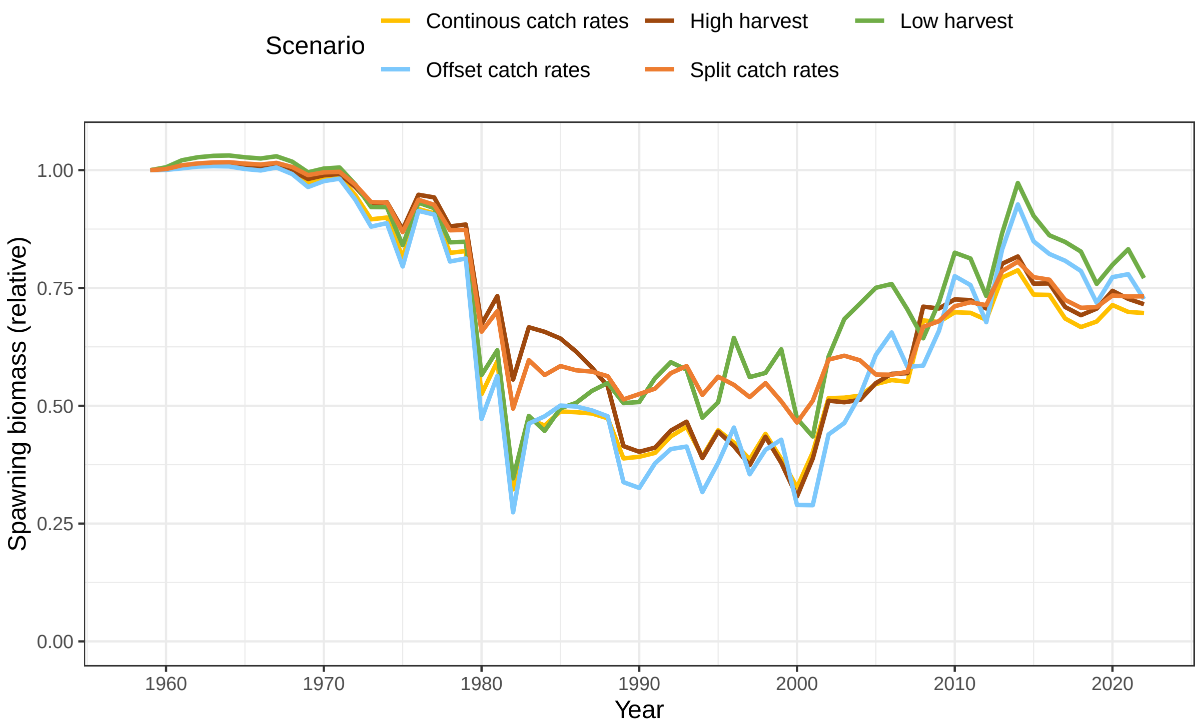


Figure G.9: Predicted biomass trajectory relative to virgin for east coast tiger prawns from 1958 to 2021, for all scenarios—the project team preferred scenario is represented by a yellow line

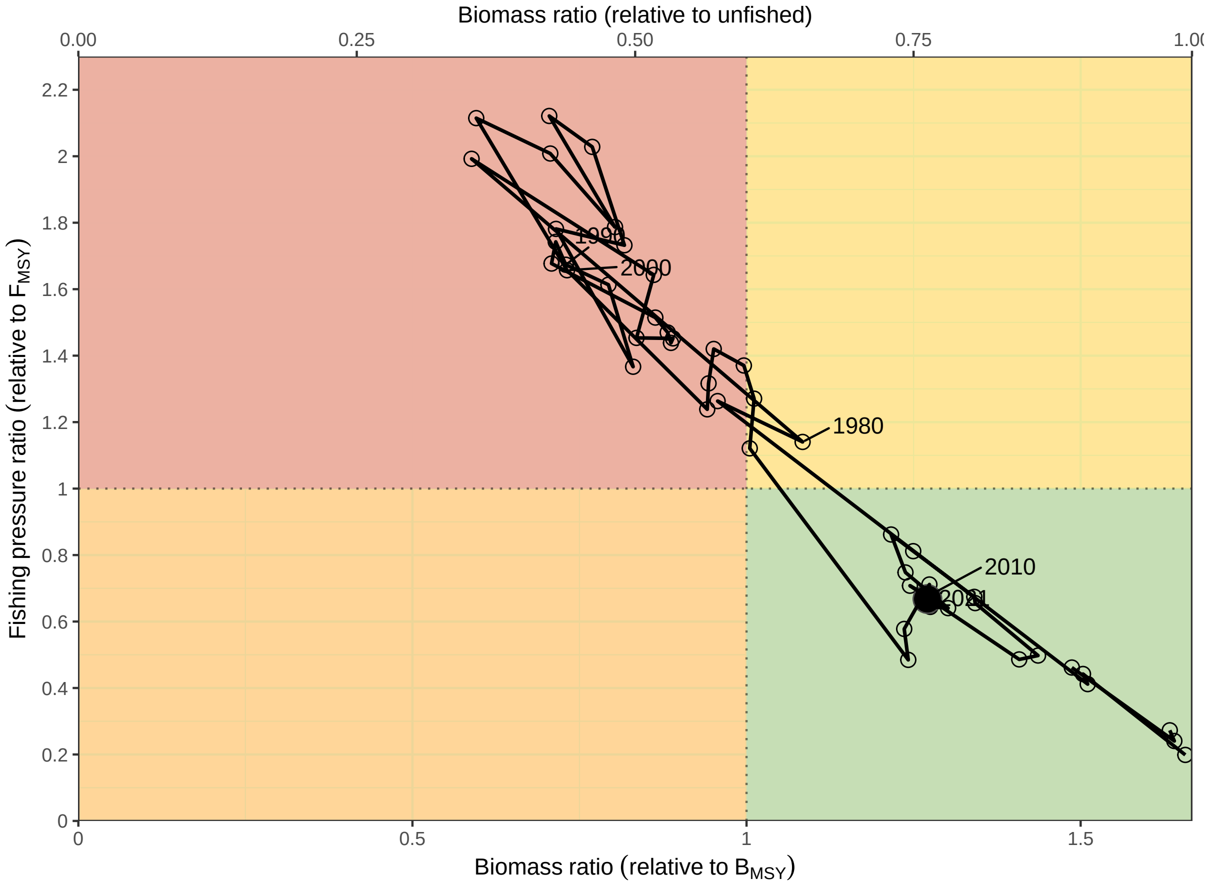


Figure G.10: Stock status indicator trajectory for tiger prawns

The equilibrium yield curve informs on the productivity of the stock at different biomass levels (Figure G.11).

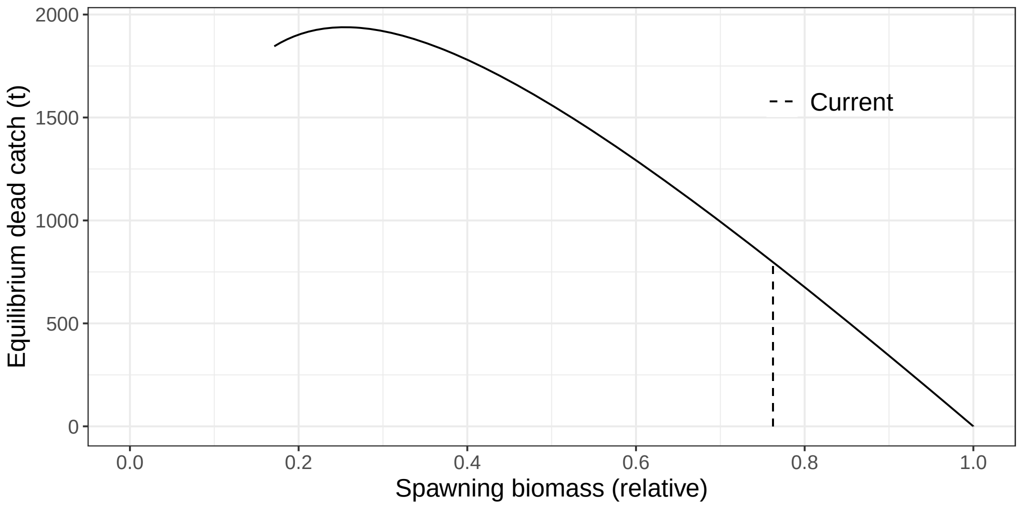


Figure G.11: Equilibrium dead catch curve for tiger prawns in the east coast of Queensland

G.4 Discussion

The Stock Synthesis model was unsuitable to assess tiger prawns for the east coast of Queensland for the following reasons:

- This application of the model resulted in unstable results, where small changes to starting conditions would prevent the model from converging or lead to drastically different results. For example, adjusting the fixed value of σ_R, the variance in recruitment, from 0.05 to 0.06 would result in a Hessian matrix that would no longer invert.
- Seasonal recruitment was estimated for the Stock Synthesis model. However, using the recommended settings as per the Stock Synthesis User Manual 3.30.20 (Methot et al. 2022), seasonal recruitment parameters hit bounds and did not estimate cleanly. To obtain clean parameter estimates the parameter bounds were sixteen times that of the recommended values from the Stock Synthesis User Manual. The requirement for parameter bounds twenty times the recommended values, as well as their unreasonably high standard deviations, formed part of the weight of evidence to not present the monthly Stock Synthesis models to the project team.
- The model took up to one hour to converge, or to fail to converge. This is likely due to the numerous parameters that are estimated in a monthly model, as well as the reporting of information on individual growth morphs. It is also possible that the long run times of the model could also be due to highly correlated parameters and the optimisation routine getting caught in local minima. Inspection of the ParamTrace.sso file did not give any indication of this although further diagnostics could indicate otherwise.
- The confidence intervals around the project team preferred biomass trajectory were unrealistically narrow. This could be mitigated by increasing the uncertainty around the catch rate model inputs.

Beyond the final models that are presented in this appendix, further modelling experiments were trialed as a way of producing a more realistic population model. Ultimately, none of these experiments resulted in a stable model that could be considered suitable for the project team preferred scenario. These experiments were:

- Exploring pseudo-seasonal modelling, as described in Methot et al. (2022) as 'Continuous seasonal recruitment', in which seasons (in this case months) appear as years. All the data and parameters are set up to treat months as if they were years. This model set up allows recruitment to be continuous across seasons, instead of an annual pulse.
- Setting up the model with a fleet for each months, allowing selectivity to be estimated for each season.
- Mirroring catchability with an offset, using a built-in feature of Stock Synthesis to mirror catchabiliity as an alternative to applying an offset to the continous catch rates in Scenario 3 outside of the model.
- Utilising the spatial modelling capabilities of Stock Synthesis, using areas as fleets, in combination with the seasonality function, to great a multi-area seasonal model. This breached the limits of what the available data could support.

Although a lot of novel work was done to push the boundaries of the Stock Synthesis software, model performance and diagnostics deemed the Stock Synthesis model unsuitable for the current stock assessment.