Stock assessment of Moreton Bay bugs (*Thenus australiensis and Thenus parindicus*) in Queensland, Australia with data to December 2021

November 2023

Queensland Government

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

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Contents

Summary

The Moreton Bay bug population on the east coast of Queensland is comprised of two species—*Thenus australiensis*, also known as the sand or reef bug, and *Thenus parindicus*, also known as the mud bug. This stock assessment indicates that the biomass of sand bug declined in the period between 1968 and 2000 to a minimum value of 67% unfished biomass. In 2021 the stock was estimated to be between 63% and 94%, and most likely at 78%, of unfished biomass. This stock assessment does not provide a clear biomass result for mud bugs.

Moreton Bay bugs are distributed throughout tropical and subtropical coastal waters of Australia from northern New South Wales to Shark Bay in Western Australia. Sand bug females reach 50% maturity at 82 mm carapace width (CW) or 59 mm carapace length (CL). Mud bug females reach 50% maturity at 75 mm carapace width or 53 mm carapace length. Both species spawn year-round with spawning peaks during the period between spring and mid-summer.

This is the first stock assessment conducted on Queensland Moreton Bay bugs.

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).

For all stocks analysed, the assessment used a one-sex monthly delay-difference population model, fitted to catch rates. Age-structured models were also trialed, however these did not lead to outcomes that were considered plausible by the project team.

For sand bugs, the data from 1968 to 2021 comprised of commercial catch and effort (1988—2021), historical commercial catch (1968–1981, 1974–1987), fishery independent survey data (2017-2021) and licence numbers (1968–2003). For mud bugs, the data from 1948 to 2021 comprised of commercial catch and effort (1988-–2021), historical commercial catch (1948–1981, 1974–1987) and licence numbers (1968–2003). The model split the fishery into two fleets to account for the rezoning of the Great Barrier Reef (GBR) in 2004—one for the commercial sector pre-July 2004, and one for commercial sector post-July 2004.

Over the last 5 years, 2017 to 2021, the Queensland total harvest averaged 605 tonnes (t) per year, including 495 t of sand bugs by the commercial sector and 110 t of mud bugs by the commercial sector (Figure 1).

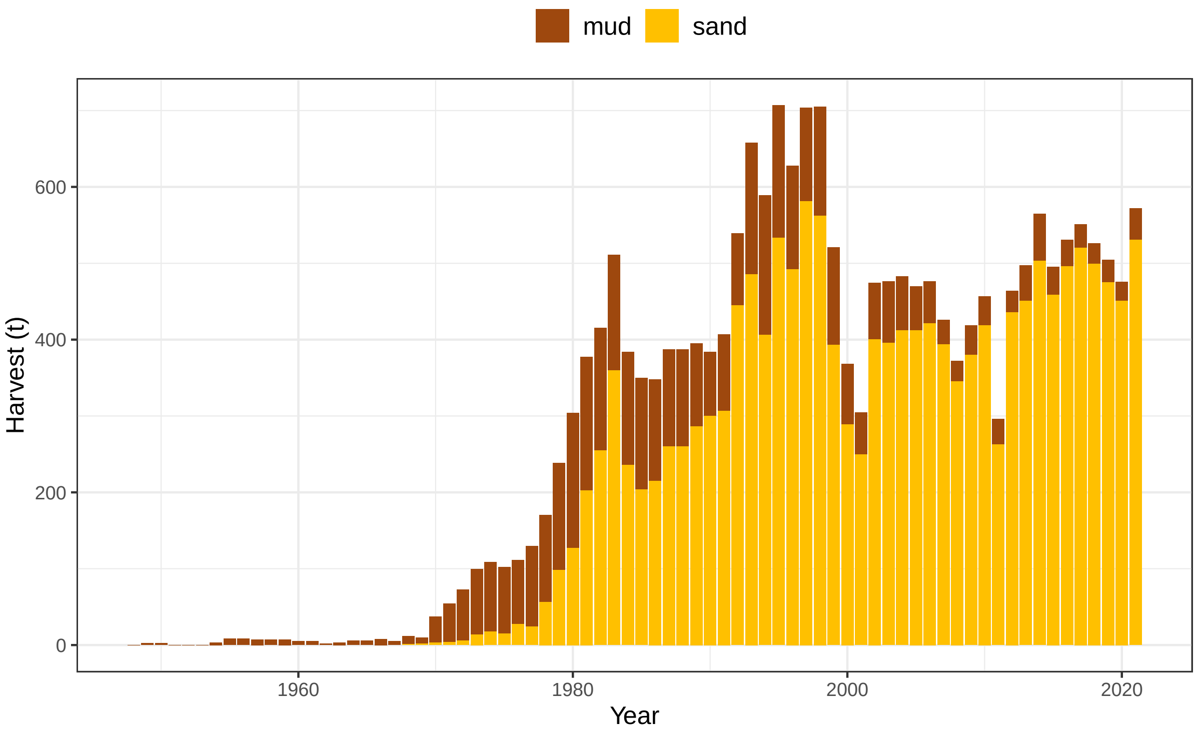

Figure 1: Annual estimated harvest (retained catch) from commercial sectors between 1948 and 2021 for sand and mud bugs combined

Commercial catch rates were standardised to estimate an index of Moreton Bay bug abundance through time (Figure 2 and Figure 4). The unit of standardisation was kilograms of bug per 'operation-day', defined to be a single day of fishing by a trawl vessel. Explanatory terms used in the standardisation model for the sand bug stocks included year, month, region, targeting behaviour, lunar phase, hours trawled, authority chain number, fraction of grid trawlable and a fishing power offset. The standardisation model for the mud bug stock included all of the aforementioned terms, except the targeting behaviour term was not preferred and only included as a sensitivity scenario. Fishery-independent survey catch rates were standardised with the following explanatory terms: strata, year, time of night and lunar phase. Survey catch rates were incorporated into the sand bug model (Figure 3).

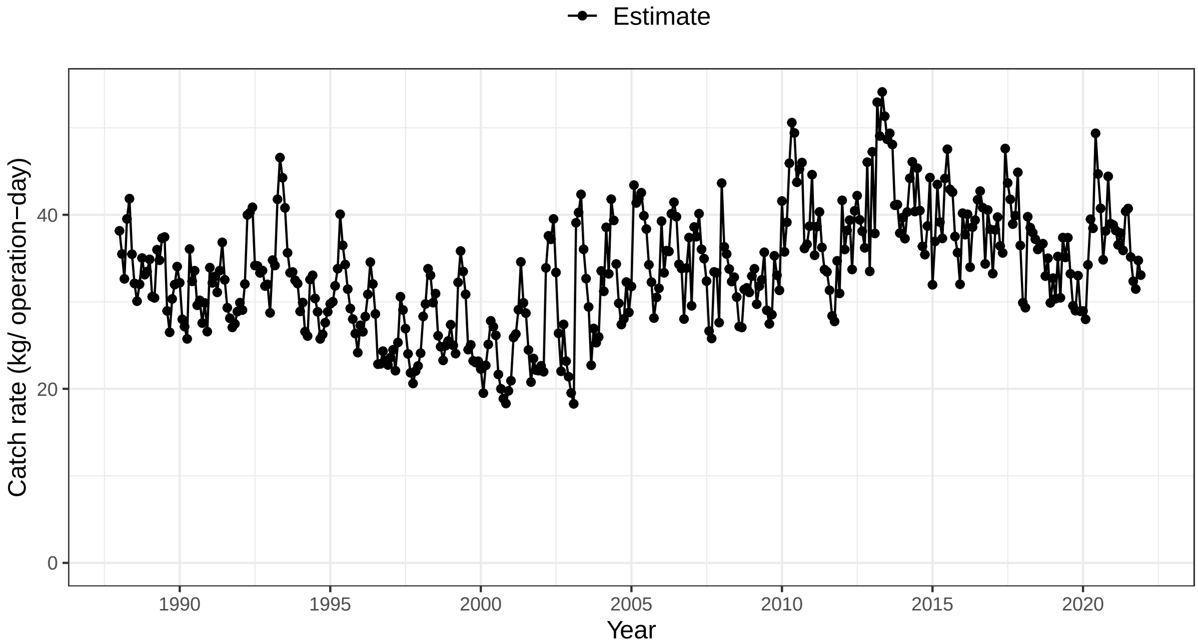

Figure 2: Standardised commercial catch rates for sand bugs between 1988 and 2021

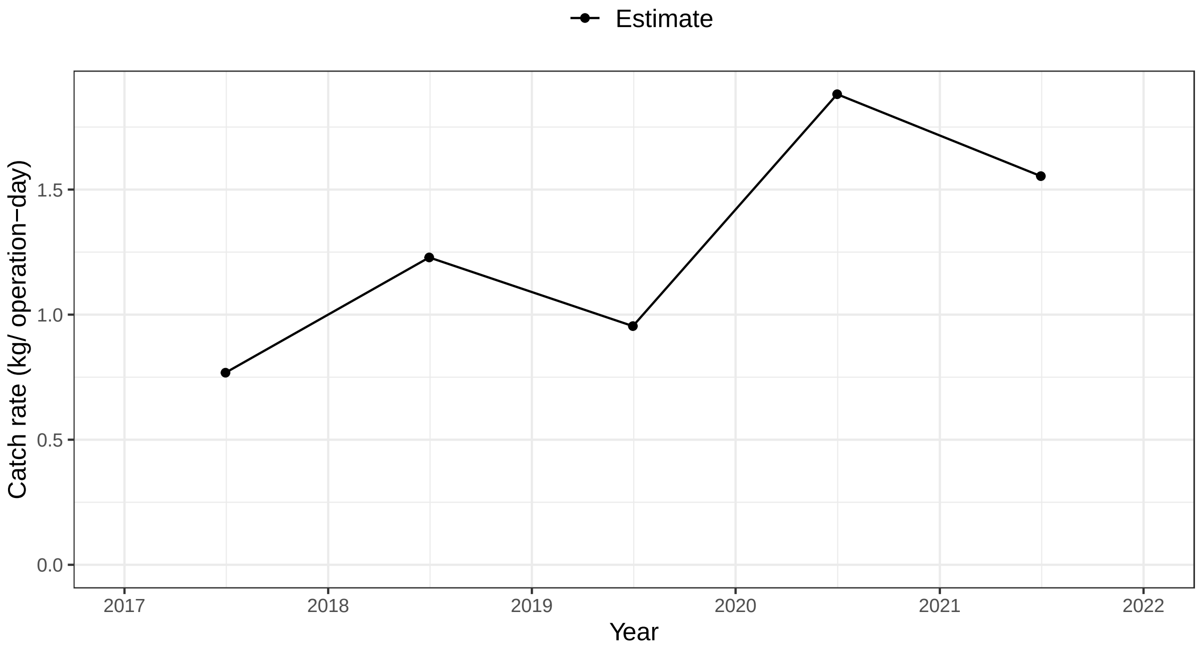

Figure 3: Standardised survey catch rates for sand bugs between 2017 and 2021

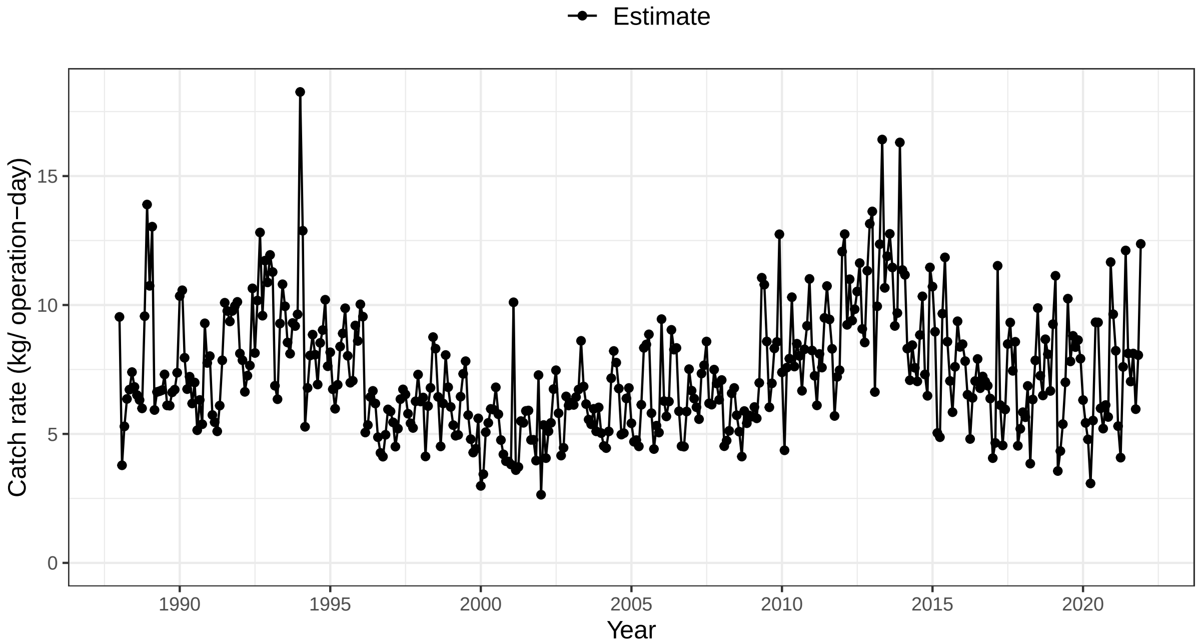

Figure 4: Standardised commercial catch rates for mud bugs between 1988 and 2021

The stock assessment was guided by a project team consisting of scientists, managers, and industry representatives. Thirteen model scenarios were run for the sand bug stock, 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 suggested that the sand bug stock experienced a decline in the period 1968 to 2000 to reach 67% of unfished biomass. The biomass has been generally increasing since, and in 2021 the stock level was estimated to be 78% (63—94% range across the 95% credible interval) of the unfished biomass (Figure 5).

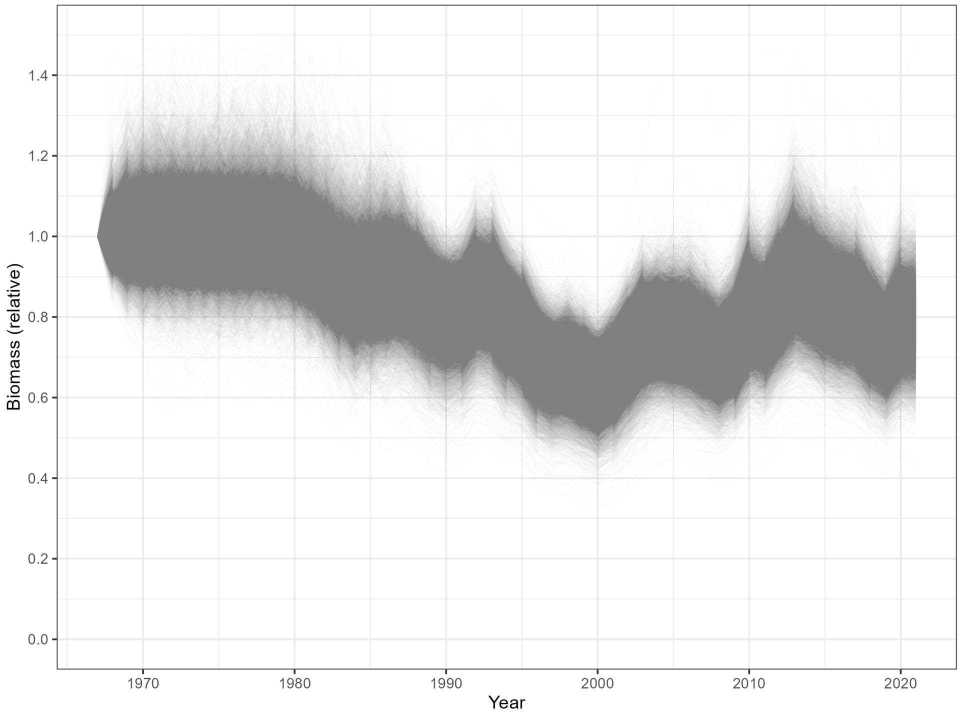

Figure 5: Predicted biomass trajectory relative to unfished, from 1968 to 2021 for sand bugs in the east coast otter trawl fishery

Thirteen model scenarios were run for the mud bug stock, covering a range of modelling assumptions and sensitivity tests. Seven scenarios had convergence problems, or diagnostics that indicated issues. The non-target nature of the fishery combined with fishery-dependent catch rates being the primary data set for model tuning makes assessment difficult. The status of the mud bug stock is undefined. The general trajectory across the thirteen scenarios shows the biomass experienced a decline from the period of 1968 until the mid 1980s, then slowly recovered since that time.

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 Moreton Bay bug stocks in 2021

Species	Indicator	Estimate
sand	Biomass (relative to unfished)	78% (63–94% credible interval)
	Biomass direction	Decreasing
	Catch	530 t
mud	Biomass (relative to unfished)	Undefined
	Biomass direction	Undefined
	Catch	42 t

Given that the delay difference models were primarily tuned against a single fishery-dependent data source (fisher catch rates), and that attempts to model the stock using additional data (e.g. length frequencies) using an age-structured modelling 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 Department, the team included three industry representatives as well as an external scientist. The project team operated under a terms of reference[1] designed to ensure a transparent and evidence-based approach. The project team members were: Industry – Rik Buckworth, Barry Ehrke and David Sterling; External Scientific Member – Clive Jones; Stock Assessment – Amanda Northrop; Animal Science Queensland – Matthew McMillan; Fishery Monitoring – Jason McGilvray; Fishery Management – Darren Roy, Lachlan Glaves and Luke Albury; Data Team – Prasadini Salgado; Ecological Risk and Policy – Marlee Kerr; Chair – Alex Campbell. The entire team is thanked for contributing their time and knowledge, and engaging constructively over the course of a sixteen months-long project.

The authors acknowledge the significant time commitment, and deep operational and technical expertise, of our industry representatives Rik Buckworth, Barry Ehrke and David Sterling. 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. (2006b), Helidoniotis (2020b), 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

CI	95% confidence interval if referring to an MLE model or 95% credible interval if referring to an MCMC model
CL	carapace length
CW	carapace width
ECOTF	East Coast Otter Trawl Fishery
DDUST	Delay-Difference with User Specified Timestep
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
FRDC	Fisheries Research and Development Corporation
GBR	Great Barrier Reef
GBRMP	Great Barrier Reef Marine Park
GLM	Generalised Linear Model
FM	Fishery Monitoring
MCMC	Markov chain Monte Carlo
MLE	Maximum likelihood estimate/estimation
MLS	minimum legal size
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
REDDUST	Random Effect Delay-Difference with User Specified Timestep
SFS	Sustainable Fisheries Strategy
SS	Stock Synthesis

1 Introduction

Two main genera of slipper lobsters, commonly known as 'bugs' (family Scyllaridae) are trawled in Queensland. The first group of bugs are the 'Balmain bugs' from the genus *Ibacus*, including *Ibacus chacei* (also known as the garlic bug), *Ibacus brucei* (also known as the honey bug), and *Ibacus alticrenatus* (also known as the velvet bug) are trawled in Queensland (Courtney et al. 2002). The second group are the 'Moreton Bay bugs' which is a collective term for two species that belong to the genus *Thenus* in Queensland (Jones 2007). This includes *Thenus australiensis* (also known as the reef or sand bug) and *Thenus parindicus* (also known as the mud bug). Both species were reclassified by Burton et al. (2007) with *Thenus australiensis* formerly known as *Thenus orientalis*, whilst *Thenus parindicus* formerly known as *Thenus indicus*. In Queensland, Moreton Bay bugs account for 80% of the landings value when compared to Balmain bugs (Courtney et al. 2002), with Moreton Bay bugs the focus of this assessment.

Moreton Bay bugs span the tropical and subtropical coast of Australia from northern New South Wales to Shark Bay in Western Australia. Latitude, depth and sediment are strong drivers of *Thenus* spp. and *Ibacus* spp. distributions within Queensland (Courtney et al. 2002; Jones 1993), providing the ability to confidently partition species. In Queensland, *T. parindicus* generally prefer shallow inshore waters between 10 and 30 m with sediment particle sizes of 0.125–0.25 mm, whilst *T. australiensis* generally prefer deeper waters between 40 and 50 m with particle sizes of 0.25–0.5 mm (Jones 1993). Only a single species of Balmain bugs, *I. chacei*, occur in relatively shallow waters (40–120 m), mainly south of 25° S (Courtney et al. 2002). Catches north of 25° S are dominated by Moreton Bay bugs (*Thenus* spp.) to a depth of around 80 m and *Ibacus* spp. at greater depths, whilst catches south of 25° S are dominated by Balmain bugs (*Ibacus* spp.) (pers comm Courtney, 2022). The remaining two *Ibacus* spp., *I. brucei* and *I. alticrenatus* occur at depths of 100–200 m and $>$250 m depth, respectively (Courtney et al. 2002). Reflecting the spatial extent of each species within the East Coast Otter Trawl Fishery (ECOTF) (see Figure 1.1), mud bugs are frequently trawled with tiger and endeavour prawns whilst sand bugs are frequently trawled with red spot king prawns in the north and saucer scallops in the south (O'Neill et al. 2006b; Jones 1988; DAF n.d.). These depth and location preferences formed the basis of splitting the commercial catch into individual species.

Studies of the movement of *Thenus* spp. in Queensland are few. Jones (1993) used the mean number of *Thenus* individuals trawled per month and variance to create an index of dispersion (variance divided by the mean) and reported two periods of higher dispersion values indicating increased aggregations of *T. parindicus* from February to June and again in October. Inversely, dispersion values remained relatively constant throughout the year for *T. australiensis*, indicating a more constant distribution (Jones 1993).

Thenus spp. display diel variability in their behaviour. During the day, laboratory studies have observed both *T. australiensis* and *T. parindicus* to bury in the sediment (Jones 1988). However, catch rates were reported to not vary with the time of day for *T. australiensis* and *T. parindicus* (Jones 1993). Jones (1993) therefore suggested individuals that are inactive and buried during the day are equally susceptible to trawl gear as those individuals that are active (generally at night). Jones (1993) hypothesized the 'tickler chain' (a heavy steel chain dragged across the benthos in front of the trawl net) was likely sufficient to disturb the top few centimetres of the benthos where inactive individuals were buried, exposing *T. australiensis* and *T. parindicus* from within the sediment to the trawl net following.

Unlike many other marine organisms such as finfish where growth is continuous, growth in crustaceans is incremental (Courtney 1997). That is, growth only occurs when associated with a moult of the exoskeleton. *T. parindicus* reach significantly smaller sizes but grow faster than *T. australiensis* (Courtney 1997). For both *T. australiensis* and *T. parindicus* growth rates do not differ significantly between sexes, but females reach significantly larger sizes than males (Courtney 1997). *T. australiensis* males and females can reach mean asymptotic sizes (*Linf*) of 77.45 mm carapace length (CL) and 89.04 mm CL, respectively (Courtney 1997). *T. parindicus* males and females can reach mean asymptotic sizes of 61.23 mm CL and 72.44 mm CL, respectively (Courtney 1997). Using a sequential tagging method, Courtney (1997) reported an annual natural mortality rate of 0.92 for both male and female *T. australiensis*. Using Pauly's (1980) estimation method, Courtney (1997) estimated the annual natural mortality rate for male and female *T. parindicus* to be 1.29 and 1.23, respectively. Maximum ages for *T. australiensis* males and females were reported as approximately 10 and 5.5 years, respectively (Courtney 1997). Maximum ages for *T. parindicus* males and females are approximately 4.5 and 5 years, respectively (Courtney 1997).

Little information is available regarding the reproduction of *T. australiensis* and *T. parindicus*. *T. australiensis* females reach 50% maturity at 82 mm carapace width (CW) or 59 mm CL (Jones 1988; Courtney 1997). *T. parindicus* females reach 50% maturity at 75 mm carapace width (CW) or 53 mm carapace length (CL) (Jones 1988; Courtney 1997). For *T. parindicus*, sex ratios remained constant at 0.5 throughout the year (Jones 1993). For *T. australiensis*, males were more prevalent throughout the year at a proportion of 0.57 (Jones 1993). Jones (1993) reported a major recruitment pulse to occur for both *T. australiensis* and *T. parindicus* during mid-summer. Low level recruitment outside the midsummer period occurred with irregular timing and magnitude (Jones 1993). Jones (1988) also noted a low but consistent occurrence of egg-bearing females throughout the year. Jones (1993) postulated that seasonal differences in larvae/juvenile mortality may have been at play transforming constant recruitment into pulse events.

Due to the overlapping habitat and similar appearance, Moreton Bay bugs are often confused with Balmain bugs. The key difference between the species is the location of the eyes. Balmain bugs have eyes positioned centrally on the carapace surface whereas the eyes of Moreton Bay bugs are positioned laterally on the outer edge of the carapace (DAF n.d.). Within the Moreton Bay bug genus, mud bugs and sand bugs are also difficult to identify but can be distinguished by their legs and colouration. Mud bugs have striped legs whilst sand bugs have speckled legs and a red/brown colouration.

Within the ECOTF, there are two separate fleets that trawl Moreton Bay bugs. The fleet operating north of 22° S primarily targets red spot king prawns, eastern king prawns, tiger prawns and sand bugs. The fleet operating south of 22° S targets scallops but in recent years has shifted to target sand bugs as scallops can not be retained in the southern inshore trawl region. In both fleets, mud bugs are likely bycatch only.

The ECOFT is currently broken into five main management regions. From north to south these include the northern, central, southern inshore, southern offshore, and Moreton Bay trawl regions (Figure 1.1).

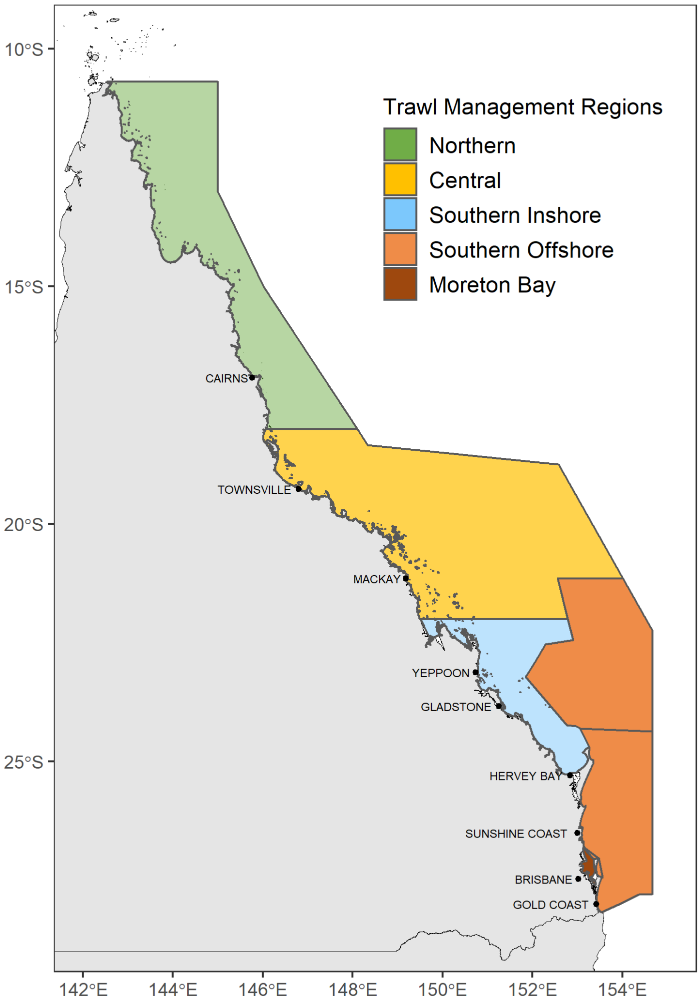

Figure 1.1: Management regions of the East Coast Otter Trawl Fishery

The ECOFT is currently managed under the *Fisheries Act 1994* and its subordinate legislation. Harvest strategies are in place for each of the five management regions (see Government 2021c, Government 2021a, Government 2021d, Government 2021e, Government 2021b). All five trawl regions have a number of management actions in place. For example, restricted entry through commercial fishing licences, effort caps on the number of nights vessels can fish, maximum vessel lengths of 20 m (maximum vessel length is 14 m in the Moreton Bay trawl region), a maximum of 120 hull units (calculated by the length, beam and depth of the hull), trawl gear restrictions (i.e., net length and mesh size) and numerous spatial and temporal closures (see *Fisheries Act 1994*). A summary of the historic management arrangements in the ECOTF that have impacted Moreton Bay bugs is in Table 1.1.

Table 1.1: History of Moreton Bay bug management in Queensland

Year	Management Change
1980	1400 licence vessels in the East Coast Trawl fishery
1988	Compulsory commercial catch logbooks implemented
1991	Prohibition on the capture of egg-bearing females (*Fishing Industry Organization and Marketing Regulations 1991*)
1995	Minimum legal size (MLS) of 6.2 cm (carapace width); no possession on a commercial fishing boat if the bug has been mutilated or had eggs removed from it (*Fisheries Regulation 1995*)
1999	Reduction to 800 licence vessels in the East Coast Trawl fishery
2000	Minimum legal size of 7.5 cm; introduction of annual southern trawl closure from 20 September to 1 November (*Fisheries (East Coast Trawl) Management Plan 1999*)
2001	Revised plan: buy back and effort management system, effort unit trading system. Introduction of an effort management system based on effort nights
2002	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. Changes to logbook reporting; separation of Moreton Bay bug and Balmain bug
2004	Reduction to 527 licence vessels. Compulsory commercial logbook reporting of gear commenced. Vessels begin use of computer mapping and GPS. Use of bycatch reduction devices and turtle exclusion devices. Rezoning of the Great Barrier Reef (GBR)
2010	Berried female Moreton Bay bugs can be retained (*Fisheries Legislation Amendment Regulation (No.4) 2009*)
2011	Maximum net length of 109 m; minimum mesh size of 75 mm (*Fisheries (East Coast Trawl) Management Plan 2010*)
2021	Changes to logbook reporting; *Thenus australiensis* (sand bug) and *Thenus parindicus* (mud bug) species are recorded separately. Implementation of regional management zones and five harvest strategies. Scallops made no-take in central and southern inshore trawl region

In 2022, the Queensland Department of Agriculture and Fisheries commenced a stock assessment for Moreton Bay bugs, specifically *T. australiensis* and *T. parindicus* on Queensland's east coast. This assessment aims to be the first formal reference point of population biomass for *T. australiensis* and *T. parindicus* individually. This assessment aims to determine current stock biomass relative to an unfished state to inform management of the ECOTF and the Status of Australian Fish Stocks (SAFS) process.

The stock was previously assessed using catch rate data only, with data through to 2019 by Helidoniotis (2020a). This assessment contains updates to data and methodology. Key updates include:

- assignment of species (i.e., sand or mud bug) to all logbook records with a location, using methodology from Fisheries Research and Development Corporation (FRDC) Project 2020/020 McMillan et al. (in press),
- stock assessment model for *T. australiensis* and *T. parindicus* separately using the Delay-Difference with User Specified Timestep (DDUST) modelling framework.

2 Methods

2.1 Data sources

Data used for DDUST population modelling of sand and mud bugs are given in Table 2.1. These data were used to form fishery dependent commercial catch rates as indices of abundance, fishery independent survey indices of abundance, and annual harvest. Data sets were compiled by calendar year at a monthly resolution. The assessment period began in 1948 for mud bugs and 1968 for sand bugs (in line with reports from Jones (1984)) and spanned until 2021 inclusive, based on available information.

Table 2.1: Data used in the Queensland east coast Moreton Bay bug stock assessment

Type	Calendar year	Source
Commercial harvest	1988–2021	Logbook data collected by Fisheries Queensland
	1963–1980	Queensland Fish Board data (Halliday et al. 2007)
	1974–1987	Htrawl voluntary harvest estimates (described in Section 8.3.7 of O'Neill et al. (2005))
	1948–1980	Commercial harvest estimates (Jones 1984)
Biological data and fishery independent survey data	2021	Biological data (sex and length from the Townsville prawn fishery) provided by Agri-Science Queensland through Fisheries Research and Development Corporation (FRDC) Project 2020/020 (McMillan et al. in press)
	1998–2006 2017–2021	Biological data (sex and length from the Queensland saucer scallop fishery) provided by Agri-Science Queensland through Fisheries Research and Development Corporation (FRDC) project 2017/048 (Courtney et al. 2021)
	1997	Biological data (growth, survival (Courtney 1997)

2.1.1 Regions

The sand and mud bug populations on the Queensland east coast were modelled as single stocks. For sand bugs, data input to the catch rate model included the northern, central, southern inshore, and the southern offshore trawl regions down to 26° S latitude (refer to Figure 1.1). Sand bug records south of 26° S latitude were excluded from catch rate analyses due to the lack of verifiable data and the anecdotal high abundance of Balmain bugs. Industry advice provided to the project suggested that sand bugs occur at approximately a 1:2 ratio with Balmain bugs south of Double Island Point. Additionally, the Fishery Monitoring (FM) survey did not extend south of Noosa (26.4° S) latitude). Therefore, there were no validated occurrences of sand bugs south of 26.4° S latitude. For mud bugs, data input to the catch rate model included the northern, central, southern inshore, Moreton Bay, and the southern offshore trawl regions down to 28° S latitude (refer to Figure 1.1). No observational data south of the southern tip of Stradbroke Island (28° S latitude) was obtained for mud bugs. For this reason, mud bug records south of 28° S latitude were excluded from catch rate analyses. The Torres Strait region was outside the scope of the species distribution modelling so the Torres Strait was excluded for both sand and mud bugs. Therefore, the spatial extent of the sand bug and mud bug stock analyses was 10–22° S and 10–28^o S, respectively.

2.1.2 Commercial

Commercial harvests of Moreton Bay bugs were recorded in the compulsory commercial logbook system from 1988 to present. The logbook system consists of daily retained catches (landed weight in kilograms) of all species from each individual fishing operator (licence). In addition to landed weight, logbooks also record such as the location of the catch (30 minute or 6 minute grid identifier), hours trawled, and trawl gear information.

Historical retained commercial catch between the start of the fishery (1968 for sand bugs and 1948 for mud bugs) and the commencement of logbooks needed to be reconstructed from other data sources. Jones (1988) provided a detailed account of the fishery from pre-1900 to 1980. The first ever Queensland Fish Board record of Moreton Bay bugs was in 1936 with 537 'bay lobster' as they were known then. The first considerable quantities (i.e., $\geq$ 2000 kg) of bay lobsters were recorded in 1948 (Jones 1988). This guided the project team's decision to begin the mud bug assessment at virgin biomass in 1948. Jones (1988) provided an annual tonnage of landed bay lobsters from 1948 to 1980. Dr Clive Jones noted the source of this data was no longer in a usable format, but revealed this data included catch from the Gulf of Carpentaria, a region external to this assessment. Therefore, the catch data from Jones (1988) was considered a likely overestimate of historic Queensland east coast catch by the project team. Alternatively, the Queensland Fish Board data and Htrawl data recorded considerably lower harvest estimates. Htrawl data were of varying quality and quantity and initially described in Section 8.3.7 of O'Neill et al. (2005). The project team considered these data sets to likely be an underestimate of historic Queensland east coast catch. Sensitivity tests were included to test the effect of the reconstruction of these data.

Industry input suggested that early catches of Moreton Bay bugs (i.e., around 1948) would have been solely comprised of mud bug, given the limited capability of vessels to work far from shore. Trawl vessels began utilising radar around 1972 (O'Neill et al. 1999). It was assumed vessels could operate offshore through the use of dan buoys from about 1968 onwards. Therefore, it was assumed that the first major harvests of sand bugs began in 1968.

2.2 Species splitting process

Sand and mud bugs exhibit strong habitat partitioning, with either species typically dominating a given location (Jones 1993; McMillan et al. in press). Only in 2021 were commercial fishers required to record their catch to species level in logbooks; prior to 2021 both species were recorded together as a multi-species complex. For this reason, a formal process was developed to allocate all commercial logbook data as either sand or mug bug prior to 2021 using the following process.

Compulsory commercial logbooks were introduced in Queensland in 1988 and are updated when necessary to reflect changing data requirements of Fisheries Queensland. Prior to 2000, Moreton Bay bugs (*Thenus*) and Balmain bugs (*Ibacus*) were recorded together in otter trawl logbooks under the category 'Bugs'. In 2000, the logbooks were updated to include separate boxes to record Moreton Bay bugs and Balmain bugs and also added a third box for 'Bugs – unspecified'. In 2005, 'Bugs – unspecified' was removed from logbooks. The otter trawl logbook released in September 2021 also required the species of Moreton Bay bugs be recorded as either sand bugs or mud bugs. As a result, logbook data from January 1988 to December 1999 needed to be separated into Balmain bugs and Moreton Bay bugs (genus level) and logbook data from January 1988 to September 2021 needed to be separated into sand bugs and mud bugs (species level).

Fisheries Research and Development Corporation (FRDC) project 2020/020 (McMillan et al. in press) was instrumental in classifying logbook records. The project, ‘Determining the spatial distribution and abundance indices for Moreton Bay bugs, *Thenus parindicus* and *Thenus australiensis* in Queensland to improve stock assessment and management’, applied a multi-step species distribution modelling (SDM) approach to allocate logbook records between *Thenus* species. The SDM enabled some separation of Moreton Bay bugs from Balmain bugs by restricting the spatial scope of Moreton Bay bug distributions to depths less than 80 m. Moreton Bay bugs rarely occur in depths greater than 80 m. Therefore, records out of the scope of the SDM (> 80 m depth) were excluded from analyses due to the high potential for these records to be Balmain bugs.

Anecdotal evidence from industry representatives working with the project noted that while the split of Balmain and Moreton Bay bugs using the 80 m depth contour was appropriate for most of the fishery, this was likely not the case south of K’gari Island. The industry representatives suggested that in South East Queensland, Balmain bugs occur as close as three nautical miles from the coast in waters less than 80 m deep. To address this concern, the species catch composition from logbook entries in 30’ grids south of K’gari Island was examined from 2005 onwards—after the genus level split and removal of ‘Bugs – unspecified’ in logbook records. For each grid, the average ratio of Moreton Bay bugs to Balmain bugs post-2005 was calculated. This ratio was used to allocate a proportion of bug catch pre-2000 to Balmain bugs which was then subsequently excluded from analyses.

Data recorded as ‘Bugs – unspecified’ from 2000 to 2005 also needed to be assigned at the genus level. By comparing the Balmain bug and Moreton Bay bug commercial logbook records after 2005 once the ‘Bugs – unspecified’ category was removed, it became apparent that both genera were harvested in approximately equal volumes in the 30’ grids south of K’gari Island . However, prior to 2005 the harvest of Moreton Bay bugs was greater than the Balmain bug harvest in the same grid cells. This suggests that from 2000 to 2005 the catch reported as ‘Bugs – unspecified’ was likely Balmain bug. Therefore, the catch data reported as ‘Bugs – unspecified’ between 2000 and 2005 in the grid cells south of K’gari Island were allocated to Balmain bugs and excluded from analyses.

From January 1988 to September 2021, the Moreton Bay bug commercial logbook records needed to be split at the species level. The SDM allocated dominant species (sand bugs or mud bugs) in each 6’ reporting grid within the spatial scope of the model. The species split for each grid from the SDM was applied to the location reported in daily commercial logbook records to categorise each Moreton Bay bug record as sand bug or mud bug.

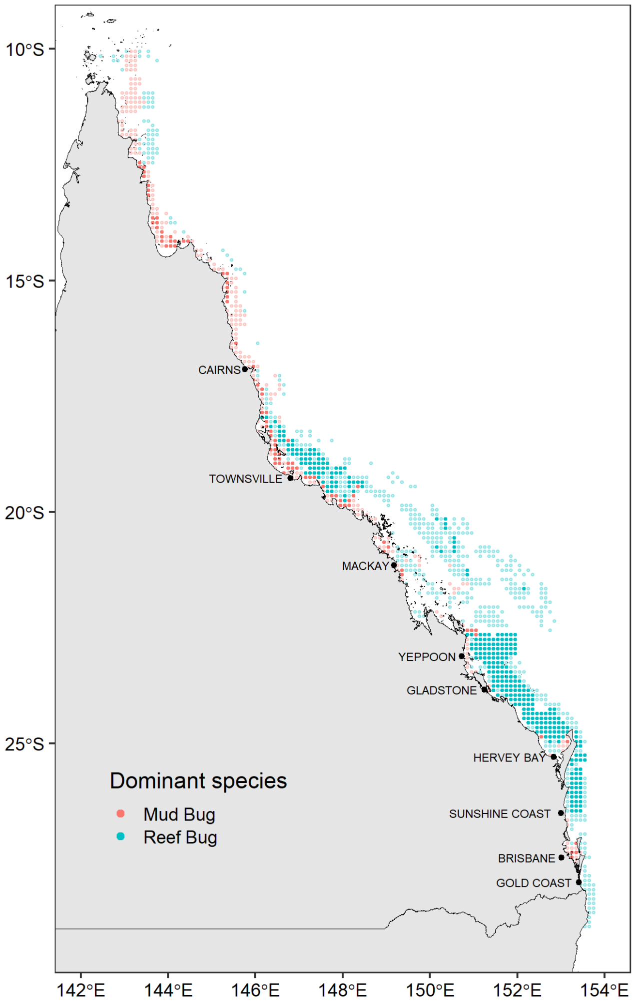

Figure 2.1: Map showing results from species distribution modelling of *Thenus* species (see McMillan et al. in press). Blue grids indicate sand bug dominance, red grids indicate mud bug dominance. Opaque grids indicate where dominant species is known (used for model training) and translucent grids indicate modelled species dominance based on species habitat preferences.

2.2.1 Recreational, Indigenous and charter

The quantity of recreational, Indigenous and charter harvests were not considered significant for Moreton Bay bugs.

2.3 Retained catch estimates

Commercial catch data were used to reconstruct the history of retained catch from 1948 until 2021 (Figure 2.2). This section describes how these data were combined to create the history of Moreton bay bug retained catch.

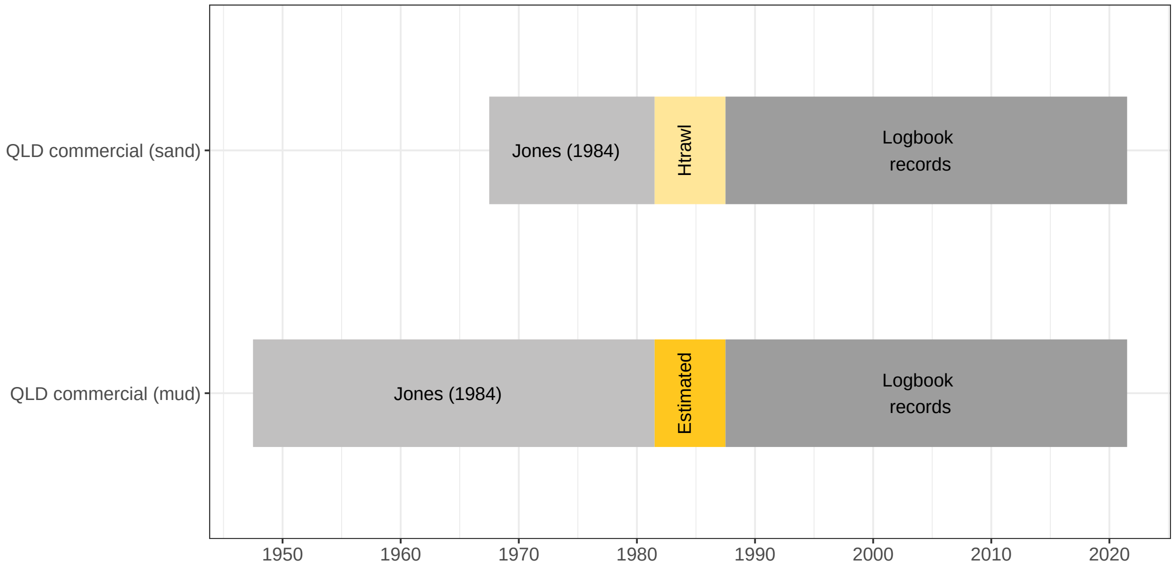

Figure 2.2: Overview of the methods used to reconstruct the history of Moreton Bay Bug harvest

Commercial retained catch:

- **1988–2021**: The retained catch of Moreton Bay bugs was calculated from retained weight of Moreton Bay bugs (in kilograms, Codes for Australian Aquatic Biota codes 28821904, 28821903, 28821007 and 28821008) recorded against trawl fishing methods in the commercial compulsory logbooks. These records were allocated to species based on the spatial distribution method developed in McMillan et al. (in press).
- **1982–1987**: Retained catch was interpolated to fill the data gap. The interpolation for sand bugs uses the Htrawl catch-per-record trend. The interpolation for mud bugs uses the number of boats in the fishery with an additional linear decrease to match Jones (1984).
- **1948–1981**: Data from Jones (1984) was split between the species using the species ratios seen in 1988–1993 of the compulsory commercial logbooks.

Estimates for all years were entered into the population model as weight in kilograms.

2.3.1 Discards

Little is known about Moreton Bay bug discards specifically but Hill et al. (1990) found crustaceans, in general, survive trawling well and have low discard mortalities. Around 51% of non-commercial crustaceans were alive 12 hours after a 30 minute exposure to air on deck. There is also anecdotal evidence that many heavily trawled tiger prawn areas close to Townsville have large populations of undersized bugs where all the adult bugs are gone (presumably harvested) suggesting the undersized bugs had also been caught before and survived being discarded. Due to the lack of data and probable low discard mortality, discards were not considered in the population model.

2.4 Standardised indices of abundance

Queensland logbook records of commercial retained catch of Moreton Bay bugs (kg whole weight) per boat per day were used as an index of legal-sized bug abundance. The index was standardised to remove the influence of a number of factors not related to abundance. This section outlines the standardisation procedure.

2.4.1 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 were removed prior to catch rate analysis in three steps. First, fishers, identified by authority chain number (ACN), who had been fishing for less than two years were excluded from catch rate analyses as their data were deemed not representative of the fishery. Second, fishers were removed from catch rate analyses if their lifetime catch contributed less than 1% of the total harvest from all fishers. These fishers are likely not representative of the fleet. Third, grids were removed from catch rate analyses if they did not contribute to the top 95% of total landings (ranked by each grid's harvest). These grids are likely not representative of the fishery.

2.4.2 Handling zero catches

Until recently, Moreton Bay bugs were typically not a primary target species in the ECOTF, likely resulting in many zero catch records. There were three situations identified whereby a fisher would record zero catch. First, the fisher caught no bugs because the fisher was targeting other species and thereby trawling unsuitable areas for Moreton Bay bugs. Second, the fisher caught no bugs despite fishing in a suitable bug area. Third, the fisher did catch bugs but not enough to fill a box. Packing practices have changed over the years but historically, fishers may have reported only full boxes which could hold around 12 kilograms. If less than a box was caught, a zero may have been recorded in the logbook. Unfortunately, these records are indistinguishable from other zeros so are not addressed in the methods. The first situation does not give insight into the abundance of Moreton Bay bugs, but the second situation does. In the case that the fisher was operating in a suitable bug area but failed to catch any bugs, the record is deemed a 'true zero' catch. In the case that the fisher was not operating in a suitable bug area and did not catch bugs, the record is deemed a 'false zero'.

Presence or absence of species typically caught or not caught with Moreton Bay bugs was used to distinguish between true and false zero records of sand and mud bugs. Sand bugs are typically caught with red spot king prawns and saucer scallops, and typically not caught with tiger, endeavour, and banana prawns. Zero catches of sand bugs were deemed 'false' if the logbook record did not contain catch of red spot king prawns or saucer scallops but did contain a significant catch of tiger, endeavour, or banana prawns. A significant catch was defined as being greater than the average catch from instances where no sand bugs were caught. Using all logbook records (1988–2021) it was found that when no sand bugs were caught, fishers caught on average 48 kg of tiger prawns, 28 kg of endeavour prawns, or 14 kg of banana prawns. If the record contained more than these average weights of tiger-, endeavour- and banana prawns and no red spot king prawns or saucer scallops, it is likely that the fisher was in an area not suitable for sand bugs. Therefore, the record would be deemed a 'false zero'. This method was verified by checking that tiger, endeavour and banana prawn catch decreased when sand bugs were reported and increased when prawns were targeted.

Mud bugs are typically caught with tiger, endeavour, and banana prawns and typically not caught with red spot king prawns and saucer scallops. Zero catches of mud bugs were deemed ‘false’ if the logbook record did not contain catch of tiger, endeavour, or banana prawns but did contain a significant catch of red spot king prawns and saucer scallops. A significant catch was defined as being greater than the average catch from instances where no mud bugs were caught. Using all logbook records (1988–2021) it was found that when no mud bugs were caught, fishers caught on average 11 kg of red spot king prawns and 17 kg of saucer scallop meat. If the record contained more than these average weights of red spot king prawns and saucer scallops, it is likely that the fisher was in an area not suitable for mud bugs. Therefore, the record would be deemed a ‘false zero’. This method was verified by checking the red spot king prawns and saucer scallop catch decreased when mud bugs were reported and increased when red spot king prawns or saucer scallops were reported.

An alternate method for characterising true zeroes from false zeroes for sand and mud bugs was explored but is not presented in this report. The method presented herein (for both sand bugs and mud bugs) provided the most contrast to the catch rate using only catches greater than zero (zero excluded model) to test pattern sensitivity in catch rates.

Table 2.2: Associated species used as indicators of zero retained catch of bugs in the catch rate analysis of commercial logbook data

Species	**Associated Species/Group**
Sand	Tiger prawn
	Endeavour prawn
	Banana prawn
Mud	Red spot king prawn
	Scallop

Table 2.3: Criteria used to distinguish false zeroes from true zeroes for sand bugs and mud bugs using all logbook data 1988–2021

Species	False zero criteria	True zero criteria
Sand	Tiger prawn catch > 48 kg OR Endeavour prawn catch > 28 kg OR Banana prawn catch > 14 kg AND Red spot king catch + Scallop meat catch =0 kg	All remaining zeroes are assumed to be true
Mud	Red spot king prawn catch > 7 kg OR Scallop meat catch > 6 kg AND Tiger, endeavour, banana prawn catch = 0 kg	All remaining zeroes are assumed to be true

After removing false zeros, records of true zeros outnumbered catch records greater than zero in the data, creating a problem of overdispersion in the generalised linear model (GLM). The overdispersion was overcome using the two-step “hurdle” method, with one model developed to explain catch vs zero catch situations, and another model developed to explain catch rates in those situations where catch occurred (i.e., excluding zero catch situations). First, the zeros were excluded and a GLM was fitted to the non-zero catch records only, using a negative binomial model for sand bugs and a quasi-poisson GLM for mud bugs. Model diagnostics indicated that the species data were better represented using these different models. Second, a two-component analysis was used whereby each record was converted to presence (1) or absence (0) depending on whether the bug catch was greater than or equal to zero. A binomial logistic model was fitted to the presence/absence data to produce annual probabilities of catching each Moreton Bay bug species. The binomial logistic model assumes that the presence/absence data (y_i) follow a binomial distribution, where $p = P(y_i = 1)$ is the probability of bugs present in the catch. The prediction (or expectation) from the binomial logistic model is:

$$\mathbb{E}(y_i) = P(y_i = 1) = p.$$

The binomial logistic model was then combined with the non-zero catch rate model, resulting in a model which accounts for the possibility of not catching any bugs. The non-zero catch rate models assume the catch data in kilograms (z_i) follow a quasi-Poisson distribution or a negative binomial distribution where the prediction (or expectation) is:

$$\mathbb{E}(z_i) = \mu.$$

To include the possibility of not catching any bugs, the expectation of z_i (how many kilograms are caught) is conditioned on y_i (whether bugs are present in the catch), and written as $\mathbb{E}(z_i|y_i)$. The law of total expectation states that

$$\begin{aligned}\mathbb{E}(z_i|y_i) &= \mathbb{E}(z_i|y_i = 1) \times P(y_i = 1) + \mathbb{E}(z_i|y_i = 0) \times P(y_i = 0)\\ &= \mu \times p + 0 \times (1 - p)\\ &= \mu p.\end{aligned}$$

Here, $\mathbb{E}(z_i|y_i = 0) = 0$ because the expected catch of bugs, given bugs are not present in the catch, is zero kilograms. To determine the catch rate which allows for the possibility of not catching any bugs, the expectation of the quasi-Poisson or negative binomial model (μ) must be multiplied by the expectation of the binomial logistic model (p).

2.4.3 Model design

Catch rates were standardised for effects of year, month, region, ACN, lunar effects, hours trawled, gear fishing power improvements, marine park rezoning and targeting behaviour.

Hours trawled provided effort information after records had been filtered to one fisher-day. Some boat-day records had missing hours trawled data, making those records incomplete. Therefore, the missing values were predicted by fitting a quasi-Poisson GLM to the complete logbook records with region, month and bug catch weight as covariates.

Fishing power refers to how adoption of technology and gear advancements improve bug 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. (2005). 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 was included in the GLMs as a log-transformed offset. ACN (authority chain number) is the unique anonymous identifier for an authority-vessel combination. By including ACN in the model, the analysis accounted for vessel operating differences that were not gear related.

Changes in marine park zoning over time could also influence catch rates. For example, the Great Barrier Reef Marine Park (GBRMP) was rezoned in 2004, resulting in decreased area open to fishing.

The closure of some areas may limit spatial access to trawling (Day et al. 2019). The fraction of each grid open to fishing in each year was calculated and included in the GLMs to account for the loss of area open to fishing.

Moreton Bay bug standardised catch rates published in 2020 identified an upward trend in standardised catch rates from 2005 onwards (Helidoniotis 2020a). This upward trend in catch rates was likely a result of shifts in fishing behaviour and reporting, as Moreton Bay bugs have become increasingly targeted due to a rise in market value and depletion of the scallop fishery. To capture this effect, a time series of wholesale price per kilogram for species prevalent in landings from the ECOTF was compiled using price data from offload receipts supplied by industry members. This market value time series was applied to catch records to identify effort targeted at Moreton Bay bugs. Industry representatives overseeing the analysis submitted a set of rules to classify targeting behaviour. Each catch record was classified as 'target' if the calculated revenue of Moreton Bay bugs was at least two times greater than the second most valuable species caught that day. If the calculated revenue was less than half the calculated revenue of the most valuable species, then the catch record was classified as 'non-target'. All other records were classified as 'seafood salad' to represent a catch record with the value of bugs similar to the value of another species.

Year, month, region, ACN, and targeting factors were included as fixed factors. Interactions between year and month, year and region and month and region were added to the model. Lunar effects were included as a numeric measure of luminance in addition to a 7-day advanced measure of luminance to capture the lunar phase. The fraction of each grid open to fishing each year was included as a numeric value between 0 and 1. The logarithm of the hours fished was also included as a numeric value. Fishing power was used as a log offset in the model.

Standardised catch rates were analysed for sand bugs using a negative binomial GLM with a logarithmic link using the R statistical environment (R Core Team 2020):

$$\log(\text{catch}) - \underbrace{\log \text{fishing power}}_{\text{offset}} \sim \text{year} \times \text{month} + \text{year} \times \text{region} + \text{month} \times \text{region} + \text{target} + \tag{2.1}$$

$$\log \text{hours} + \text{lunar} + \text{lunar advanced} + \underbrace{textACN}_{\text{random}} + \log \text{fraction trawlable} \tag{2.2}$$

Standardised catch rates were analysed for mud bugs using a quasi-Poisson GLM with a logarithmic link using R software (R Core Team 2020):

$$\log(\text{catch}) - \underbrace{\log \text{fishing power}}_{\text{offset}} \sim \text{year} \times \text{month} + \text{year} \times \text{region} + \text{month} \times \text{region} + \tag{2.3}$$

$$\log \text{hours} + \text{lunar} + \text{lunar advanced} + \underbrace{textACN}_{\text{random}} + \log \text{fraction trawlable} \tag{2.4}$$

The annual catch rate values were predicted using the last five years of active ACNs (169 total for sand bugs, 239 total for mud bugs), the mean hours spent trawling from the last five years (11.4 hours for sand bugs, 10.8 hours for mud bugs), the mean fishing power offset from the last five years (1.051 for sand bugs, 1.004 for mud bugs), the mean fraction of each grid cell open to fishing since 2004 (0.71 for sand bugs, 0.43 for mud bugs) and was weighted by the month, region and target factor. The marginal prediction took the influence of the data imbalance into account and formed weightings for factors other than year and month. The weightings were multiplied to the model predictions to output weighted model predictions. Then, the monthly catch rates were generated by aggregating the weighted model predictions over the other factors.

2.4.4 Fishery-independent survey

Fisheries Queensland's Fishery Monitoring (FM) has periodically run a fishery-independent survey of the saucer scallop fishery from Gladstone to Hervey Bay since 1997 (Dichmont et al. 2000), encompassing one of the two main Moreton Bay Bug fishing grounds. Useful Moreton Bay bug length and density data has also been collected in this survey since 1998. The survey ran annually, with extensive sampling between 1997–2000 and 2017–2022. Surveys between 2001 and 2006 were limited to the Scallop Replenishment Areas (SRAs) and a single stratum. No surveys were undertaken between 2007 and 2016. The survey occurs primarily in October each year, prior to the opening of the saucer scallop season. Between 2001 and 2006, the survey was redesigned twice to account for changes in management over this period, including the implementation of a rotational harvest strategy in the SRAs and changes to the GBRMP zoning in 2004. From 2017 onwards, the survey was extended to include strata off K'gari Island and the Sunshine Coast to capture possible range shifts in saucer scallops.

Although information on bug species has been recorded incidentally since 1998, changes to the survey design, sampling effort and distribution, area closures (marine protected areas), and gear used (e.g., introduction of bycatch reduction devices and turtle exclusion devices) during the first phase of the survey to 2006 result in more comparable data being available for the second phase of the survey from 2017 onwards when all these aspects were standardised. McMillan et al. (in press) investigated the data from the FM survey to assess Moreton Bay bug population trends.

McMillan et al. (in press) produced standardised catch rates to account for differences in sampling strata, year, time of night, and lunar phase using a quasi-Poisson GLM. Due to the limited distribution of mud bugs present in a small number of strata in the FM dataset, catch rate modelling was conducted on sand bugs only, which dominated the dataset and were widely distributed among strata. The model used catch as the response variable (count data) with strata, year, time of night and lunar phase as explanatory variables. The natural logarithm of swept area and calibration factor were used as offsets. ANOVA tests were used to determine if explanatory variables made significant contributions to the model. Predicted mean catch rates were calculated using mean values for explanatory variables. Modelling was performed in the R statistical environment (R Core Team 2020).

2.5 Fishing power estimation

Fishing power estimates were based on Queensland ECOTF 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. (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 Moreton Bay bug 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 chain, number of nets, trawl speed and horsepower. Prior to 2004, gear information was collated by O'Neill et al. (2006b). In 2006, gear description sheets were introduced in the ECOTF logbooks. Fishing power in 2005 was taken as the average of 2004 and 2006 fishing power estimates due to a lack of gear information in 2005. Fishing power 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):

$$\begin{aligned}\log(\text{weight}) \sim & \text{year} \times \text{month} \times \text{grid} + \text{lunar} + \text{lunar advance} + \log(\text{hours}) + \log(\text{HP}) + \\ & \log(\text{speed}) + \text{net type} + \text{ground gear} + \text{boards} + \text{BRD} + \text{TED} \\ & + \text{GPS} + \text{computer mapping}\end{aligned}$$

where:

- log(weight) is the log transform of weight of sand or mud bugs in kilograms,
- fishing year (year) and fishing month (month) relate to the fishing season for Moreton Bay bugs which is the same as calendar year,
- lunar is the luminosity of the moon, lunar advance (lunar advance) differentiates whether the lunar phase was waxing or waning,
- log(hours) is the log transform of the hours fished per boat per day,
- log(HP) is the log transform of engine rating in horsepower,
- log(speed) is the log transform of trawling speed,
- net type, ground gear and boards are factors representing type of net, ground gear and boards used, and
- BRD, TED, GPS and computer mapping are binary variables representing the presence of bycatch reduction devices and turtle excluder devices, 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.

2.6 Biological information

Important biological sex, length, maturity, growth and fecundity data were provided by Agri-Science Queensland through FRDC funded projects 2020/020, 2017/048 and 1992/102 (McMillan et al. in press; Courtney et al. 2021; Courtney 1997). Project 2020/020 aimed to determine the spatial distribution for Moreton Bay bugs, *Thenus parindicus* and *Thenus australiensis* in Queensland to improve stock assessment and management. Project 2017/48 aimed to improve mortality rate estimates for saucer scallops but also collected length and sex data for Moreton Bay bugs. Project 1992/102 provided biological data associated with yield optimisation such as growth, movement and mortality rates.

2.6.1 Carapace width and length

Minimum legal size (MLS) restrictions imposed by fishery management currently use carapace length but historically used carapace width. The following formula was used to relate carapace length (CL) to carapace width (CW), both measured in millimeters (Milton et al. 2006) for sand bugs and mud bugs:

$$CW = 1.7623CL^{0.9429}. \tag{2.5}$$

2.6.2 Fecundity and maturity

Female batch fecundity (number of eggs) was based on the relationship estimated by Jones (1988):

$$\text{number of eggs}_{\text{sand}} = -67.049 + 12.732CL \quad (2.6)$$

$$\text{number of eggs}_{\text{mud}} = -26.329 + 6.587CL. \quad (2.7)$$

The population model assumes that bugs are recruited into the fishery at 24 months.

A monthly spawning pattern vector was sourced from Jones (1988) and applied to both species.

$P_{\text{spawning}} = [0.075, 0.097, 0.026, 0.021, 0.014, 0.010, 0.005, 0.060, 0.218, 0.206, 0.196, 0.071]$

The proportion of males and females in the population was assumed to be equal.

2.6.3 Weight-length

The following formulae were used for converting carapace length CL (cm) to weight W (kg):

$$W_L = \alpha \times L^{\beta} \quad (2.8)$$

$$\log(W_{\text{sand, female}}) = -7.42222 + 2.99512 \log(CL), \quad (2.9)$$

$$\log(W_{\text{sand, male}}) = -7.18890 + 2.93551 \log(CL), \quad (2.10)$$

$$\log(W_{\text{mud, female}}) = -7.73111 + 3.09121 \log(CL), \quad (2.11)$$

$$\log(W_{\text{mud, male}}) = -7.39741 + 2.99223 \log(CL). \quad (2.12)$$

The formula coefficients were estimated using the least squares best fit on data collected by Jones (1988) from 1983 to 1987 off Cairns, Townsville and Swain reefs. Coefficient estimates agree with those found by Milton et al. (2006).

2.6.4 von Bertalanffy growth

Von Bertalanffy growth curve parameters were sourced from Courtney (1997) and Jones (1988). These parameters were based on the relationship:

$$L_a = L_\infty(1 - e^{-\kappa(a-t_0)}) \quad (2.13)$$

where L_a is the length of an individual at age a in years. Sex-specific parameters are shown in Table 2.4.

Table 2.4: Von Bertalanffy growth curve parameters for sand and mud bugs from Courtney (1997)

Species	Sex	L_∞ $(cm\,CL)$	κ $year^{-1}$	t_0 $year^{-1}$
Sand	Female	8.904	0.584	0
	Male	7.745	0.511	0
Mud	Female	7.244	0.840	0
	Male	6.123	0.949	0

Growth was not sex-specific in the model. Therefore, estimates from Courtney (1997) in Table 2.4 were averaged across sexes. This resulted in L_∞ estimates of 8.325 cm and 6.684 cm CL and κ estimates of 0.548 year^{-1} and 0.894 year^{-1} for sand and mud bugs, respectively.

Table 2.5: Von Bertalanffy growth curve parameters for sand and mud bugs from Jones (1988)

Species	L_∞ $(cm\,CL)$	$\kappa\ year^{-1}$	$t_0\ year^{-1}$
Sand	15.2	0.27	-0.44
Mud	9.1	0.73	-0.21

Growth estimates differed considerably between Courtney (1997) and Jones (1988). Estimates of L_∞ were significantly larger in Jones (1988). Growth parameters from Courtney (1997) and Jones (1988) were both modelled. Survey data collected from McMillan et al. (in press), the Department of Agriculture and Fisheries (DAF) FM Scallop Survey, and limited survey data from Jones (1988) found few individuals over 100 mm CL. Given L_∞ is the average maximum size (rather than the absolute maximum size) and the available length data has very few individuals over 100 mm CL, experts from the project team preferred parameters from Courtney (1997).

2.6.5 Deriso-Schnute growth

Growth within the population model (Equation 2.14) follows Schnute's extension of the Ford growth equation (Quinn et al. 1999, page 215, Equation 5.14) and is represented by weight at recruitment W_r, weight at the timestep before recruitment W_{r-1} and the parameter ρ.

$$W_a = W_{r-1} + (W_r - W_{r-1})\,\frac{1-\rho^{1+a-r}}{1-\rho} \tag{2.14}$$

The parameter ρ can be 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.

$$\rho = 1 - (W_r - W_{r-1})\,/\,(W_\infty - W_{r-1}) \tag{2.15}$$

Before ρ can be calculated, W_∞, W_r and W_{r-1} must be determined. These weights at age were found using the following steps:

1. Average the growth parameters from Table 2.4 across sexes
2. Find length at age L_a using Equation 2.13 for each species using the averaged parameters
3. Find weight at age by substituting L_a into Equation 2.8 for each species. The age chosen for W_∞ is 10 for sand bugs and mud bugs.

Moreton Bay bugs are recruited to the fishery at around $r = 24$ months of age (Section 2.6.2). Resulting growth parameters determined for the model are shown in Table 2.6.

Table 2.6: Deriso-Schnute growth parameters for Moreton Bay bugs

Species	Parameter	Value
Sand	W_∞	0.347
	W_{r-1}	0.102
	W_r	0.109
	ρ	0.971
Mud	W_∞	0.194
	W_{r-1}	0.109
	W_r	0.114
	ρ	0.941

2.6.6 Mortality

Natural mortality estimates were sourced from Courtney (1997). For sand bugs natural mortality estimates were based on a field tag re-capture study using the Ricker (1975) sequential tagging method. For mud bugs natural mortality estimates were based on maximum ages fed into Equation 11 from Pauly (1980) based on a multiple regression analysis of 175 fish stocks. Sex-specific parameters are shown in Table 2.7.

Table 2.7: Natural mortality estimates from Courtney (1997)

Species	Sex	M $year^{-1}$
Sand	Female	0.92
	Male	0.92
Mud	Female	1.23
	Male	1.29

Mortality was not sex-specific in the model. Therefore, for sand bugs natural mortality was input as 0.92 year^{-1}. For mud bugs, natural mortality was entered as an average of males and females estimates at 1.26 year^{-1}.

2.7 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. (2006a), Courtney et al. (2014a), O'Neill et al. (2014), and Helidoniotis (2020c) and a technical description can be found in Appendix E. 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 F). Population model methods and results in the main body of this report relate only to the DDUST models.

2.7.1 Model specification

The delay-difference population model was fitted to the data to determine the biomass of Moreton Bay bugs in each year. The model (Equations 2.16 and 2.17) operated on a monthly time step t:

$$B_t = (1+\rho)s_{t-1}B_{t-1} - \rho s_{t-1}s_{t-2}B_{t-2} - \rho s_{t-1}w_{r-1}R_{t-1} + w_r R_t, \tag{2.16}$$

$$N_t = N_{t-1}s_{t-1} + R_t, \tag{2.17}$$

where B_t was the exploitable biomass of Moreton Bay bugs (kg), ρ was the Brody growth coefficient, s_t was bug 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 bugs at age a (in kg) and R_t was the number of newly recruited bugs. For a technical description of the delay-difference model refer to the Appendix E or Deriso (1980) and 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. 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. 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.

2.7.2 Model assumptions

The main assumptions of the delay-difference model were:

- growth in mean body weight at age is described by Deriso-Schnute growth (Equation 2.14),
- 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,
- recruitment occurs before catch in each timestep,
- catch rates were proportional to abundance,
- age at first recruitment to the fishery was equal to twenty four months,
- mean growth function for bug weight used parameters for both sexes combined,
- there was a 50/50 sex ratio,
- the stock-recruitment relationship can be described by the Beverton-Holt equation,
- the fishery began from an unfished state in 1948 for mud bugs and 1968 for sand bugs,
- the instantaneous natural mortality rate does not depend on size, age, year or sex, and
- dynamic pool (the stock is homogeneously mixed) (Shepherd et al. 2002).

2.7.3 Model parameters

A variety of parameters were included in the model, with some of these fixed at specified values and others estimated.

The transformed initial recruitment, R_{init} was estimated within the model. The initial recruitment has the following relationship to R_{init}: $R_0 = \exp(R_{\text{init}})$.

Beverton-Holt stock recruitment steepness, h, was also estimated within the model through the parameterisation

$$h = \frac{1 + \exp(\xi)}{5 + \exp(\xi)}, \tag{2.18}$$

developed in O'Neill et al. (2014). 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 general, steepness is around 0.7 for the fish families such as Sebastidae, Scombridae and Salmonidae (Thorson 2020). For Moreton Bay bugs, there is no information around the value of steepness so it was assumed that the value would sit somewhere around 0.5 with a very weak prior so the model had a lot of flexibility to estimate the steepness value. However, it is unlikely the Moreton Bay bug population have ever dropped below 20% so the reproductivity at this level is more-or-less unknown. In addition, the low contrast catch rates (refer to Figure 3.9

and 3.10) do not have strong trends of decline nor recovery to assist in the estimation of steepness. For this reason, the model may produce a steepness value that is unlike the true biology of the population.

Parameters of the Deriso-Schnute growth relationship were fixed at the values in Table 2.6.

Natural mortality (M) was fixed in the model at the values in Table 2.7.

Seasonal recruitment parameters, κ and μ and seasonal catchability parameters, q_1 and q_2 were estimated in the model. A normal prior was used for κ and μ with details in Table 2.8. No priors were used for q_1 and q_2.

Table 2.8: Model parameters with associated priors, prior standard deviations and prior types

Parameter	Species	Min	Mean	Std. Dev.	Type
σ_R	sand	0.2	-	-	-
	mud	0.17	-	-	-
R_{init}	sand	-	-	-	-
	mud	-	-	-	-
ξ	sand	-	log(3)	1	Normal
	mud	-	log(3)	1	Normal
κ	sand	-	5	1	Normal
	mud	-	0.5	100	Normal
μ	sand	-	0	1	Normal
	mud	-	-2	100	Normal
q_1	sand	-	-	-	-
	mud	-	-	-	-
q_2	sand	-	-	-	-
	mud	-	-	-	-

Recruitment deviations between the start of the fishery (1948 for mud bugs and 1968 for sand bugs) and 2021 improved fits to abundance indices as annual variability in recruitment allowed for changes in the population on shorter time-scales than fishing mortality alone.

2.7.4 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 (Kristensen 2023) which enables Stan (Stan Development Team 2022) 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., Figures B.86.

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.1–B.26 and Table 3.1.

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.

2.7.5 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:

- **Rezoning**: In July 2004, major revisions to the GBRMP zoning occurred. There was speculation that this may have impacted the ability to catch Moreton Bay bugs and bring bias to the indices of abundance. To adjust for the rezoning, the indices of abundance were split into two fleets, pre-July 2004 and post-July 2004, with each fleet associated with a different catchability coefficient. The catchability coefficient is the link between indices of abundance and actual modelled biomass. Ultimately, the model which split the indices of abundance into two fleets was preferred by the project team and the the model with a single continuous time series of indices of abundance was included as a sensitivity scenario.
  - Split: the indices of abundance were split into two fleets, pre-July 2004 and post-July 2004, with separate catchability coefficients.
  - Continuous: the indices of abundance were a single continuous time series with a single catchablity coefficient.
- **Historical retained catch data**: Prior to the introduction of daily logbooks in 1988, the retained catch data were collected from the commercial sector via the Queensland FishBoard and reconstructed using Htrawl catch-per-record data and number of boats as proxies for harvest. As such, there was some uncertainty around the true historical harvest data. As a sensitivity test, a multiplier was applied to the Queensland FishBoard retained catch data in a number of scenarios as well as pattern sensitivity.
  - 100%: Historical harvest data reconstructed by project team
  - Pattern: Alternative historical harvest data reconstructed by project team
  - 75%: Reconstructed data multiplied by 0.75
  - 125%: Reconstructed data multiplied by 1.25
- **Natural mortality (M)**: Natural mortality estimates from Courtney (1997) were preferred by the project team. However, some disagreement between the estimates using the Ricker (1975) sequential tagging method and Pauly (1980) linear regression method suggest uncertainty around the exact values. Two sensitivity scenarios for each species were included to test a lower and higher natural mortality.
  - Low: 0.72 yr^{-1} for sand bugs and 1.06 yr^{-1} for mud bugs
  - Mid: 0.92 yr^{-1} for sand bugs and 1.26 yr^{-1}f or mud bugs
  - High: 1.12 yr^{-1} for sand bugs and 1.46 yr^{-1} for mud bugs
- **Standard error of the catch rate data (σ_I)**: The population model uses the abundance indices as data. Thus, any additional process error (error resulting from model specification) and observation error needs to be included with the indices when given to the population model. For this reason, the standard error of the abundance indices was fixed at 0.2 for sand bugs and 0.5 for mud bugs. The standard error values were also increased and tested as sensitivity scenarios. These scenarios

represent a model which relies less on recruitment deviations to fit to the indices of abundance and may provide a model that is less likely to be overfit.

  - Project team preferred: $\sigma_I = 0.2$ for sand bugs and $\sigma_I = 0.5$ for mud bugs
  - Alternative case: $\sigma_I = 1.5$ for sand bugs and $\sigma_I = 1.5$ for mud bugs

- **Timestep**: Two options for the time step used in the model were considered.
  - Annual
  - Monthly
- **Seasonal catchability**: Both the sand bug and mud bug indices of abundance showed intra-annual (seasonal) variability, suggesting there may be unaccounted for monthly impacts on either biomass or catchability. Whether the seasonal variability is truly fluctuating abundance or some unmeasured covariate, the seasonal catchabality pattern allowed the model to vary the relationship between the indices of abundance and biomass (often referred to as catchability and represented as q). A sensitivity scenario (Scenario 10 for both species) was included where the seasonal catchability parameters q_1 and q_2 were fixed to values that forced the model fit to be as extreme as the high peaks and low pits of the monthly catch rate timeseries data.
- **Alternative growth curves**: Two sources of information on growth were available for the present assessment: Jones (1988) and Courtney (1997). The main difference being the much larger estimates of mean maximum asymptotic size (L_{inf}) reported by Jones (1988). Growth coefficients from both sources are as follows:
  - Courtney sand bug growth: L_∞ = 8.325 cm CL, κ = 0.548, $t0$ = 0
  - Jones sand bug growth: L_∞ = 15.2 cm CL, κ = 0.27, $t0$ = -0.44
  - Courtney mud bug growth:L_∞ = 6.684 cm CL, κ = 0.894, $t0$ = 0
  - Jones mud bug growth: L_∞ = 9.1 cm CL, κ = 0.73, $t0$ = -0.21

Thirteen combinations of sensitivities were tested, as outlined in Table 2.9 and Table 2.10. The project team's preferred scenario has been named Scenario 1. Other scenarios are numbered in an arbitrary order based on different parameter settings and do not represent a rank of plausibility.

Table 2.9: Table of scenarios tested to determine sensitivity to parameters, assumptions and model for sand bugs

Scenario	Rezoning	Harvest	Natural mortality	$\sigma_I^\star$	Timestep	q_1, q_2	Growth curve
1 (Project team preferred)	Split	100%	0.92	0.2	Monthly	Estimated	Courtney
2	Continuous	100%	0.92	0.2	Monthly	Estimated	Courtney
3	Split	100%	0.72	0.2	Monthly	Estimated	Courtney
4	Split	100%	1.12	0.2	Monthly	Estimated	Courtney
5	Split	Pattern	0.92	0.2	Monthly	Estimated	Courtney
6	Split	75%	0.92	0.2	Monthly	Estimated	Courtney
7	Split	125%	0.92	0.2	Monthly	Estimated	Courtney
8	Split	100%	0.92	1.5	Monthly	Estimated	Courtney
9	Split	100%	0.92	0.2	Annual	Estimated	Courtney
10	Split	100%	0.92	0.5	Monthly	Fixed	Courtney
11	Split & Survey	100%	0.92	0.2	Monthly	Estimated	Courtney
12	Split	100%	0.92	0.2	Monthly	Estimated	Jones
13	Split & Data Filter$^\diamond$	100%	0.92	0.2	Monthly	Estimated	Courtney

* σ_I is the standard error of the standardised catch rate data.
$^\diamond$ Data were filtered to include only records classified as target. This method of filtering is likely to cause hyperstability in the population model. Filtered data was then re-fit to catch rate model.

Table 2.10: Table of scenarios tested to determine sensitivity to parameters, assumptions and model for mud bugs

Scenario	Rezoning	Harvest	Natural mortality	$\sigma_I^\star$	Timestep	q_1, q_2	Growth curve
1	Split	100%	1.26	0.5	Monthly	Estimated	Courtney
2	Continuous	100%	1.26	0.5	Monthly	Estimated	Courtney
3	Split	100%	1.06	0.5	Monthly	Estimated	Courtney
4	Split	100%	1.46	0.5	Monthly	Estimated	Courtney
5	Split	Pattern	1.26	0.5	Monthly	Estimated	Courtney
6	Split	75%	1.26	0.5	Monthly	Estimated	Courtney
7	Split	125%	1.26	0.5	Monthly	Estimated	Courtney
8	Split	100%	1.26	1.5	Monthly	Estimated	Courtney
9	Split	100%	1.26	0.5	Annual	Estimated	Courtney
10	Split	100%	1.26	0.5	Monthly	Fixed	Courtney
11†	Split	100%	1.26	0.5	Monthly	Estimated	Courtney
12	Split	100%	1.26	0.5	Monthly	Estimated	Jones
13	Split & Data Filter$^\diamond$	100%	1.26	0.5	Monthly	Estimated	Courtney

* σ_I is the standard error of the standardised catch rate data.
† An extra scenario with targeting incorporated in the catch rate standardisation. All other settings match Scenario 1. This was not tested for sand bugs because the preferred sand bug model has targeting in the catch rate standardisation.
$^\diamond$ Data was filtered to exclude records that had residuals beyond the upper quartile (1.5249) in the catch rate standardisation model. Filtered data was then re-fit to the catch rate model.

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 Moreton Bay bug stocks. The project team decided that different catchabilities before and after the rezoning of the GBR was an appropriate representation of the fishery so the split catch rates were preferred. The historical harvest reconstruction used a suite of data sources including Jones (1984), voluntary Htrawl and fishing licence counts. The resulting reconstruction was accepted by the project team but due to the uncertainty, the magnitude and pattern of the harvests were sensitivity tested (refer to Section 2.3 for more information). Natural mortality estimates were published in Courtney (1997) using two methods, tag re-capture and an empirical equation from Pauly (1980) to derive natural mortality from the maximum observed age. Indirect estimates of natural mortality such as those derived from Pauly (1980) have been shown to be inaccurate (Newman et al. 1996; Pascual et al. 1993). Therefore, the project team preferred the tag-recapture results published in Courtney (1997). The standard error of the standardised catch rate data was chosen by report authors to help with model fitting. The values 0.2 for sand bugs and 0.5 for mud bugs gave a smooth fit of the catch rate data such that the fits were not overly tight. The monthly timestep was preferred by the project team as it could capture biological processes on a smaller scale and account for seasonal changes in catchability and recruitment. It was preferred that the seasonal catchability parameters were estimated for the same reasons that the monthly timestep was chosen. Two different growth curves were available for sand and mud bugs. The growth curves in Courtney (1997) were preferred because they were more recent and more closely reflected lengths from length frequency data (see F.5.1.4) The Jones (1988) growth curve was added as a sensitivity test. These preferences were expressed through project team meetings. The decisions of these meetings are presented in Appendix D.

3 Results

Model inputs are described for the sand and mud species of Moreton Bay bugs. Model outputs relate to Scenario 1 for sand bug as defined in Table 2.9. Results from all other scenarios are presented in Appendix B.1 and B.2. .

3.1 Model inputs

3.1.1 Data availability

Figure 3.1 summarises the assembled data sets input to the model for the sand bug and mud bug stocks.

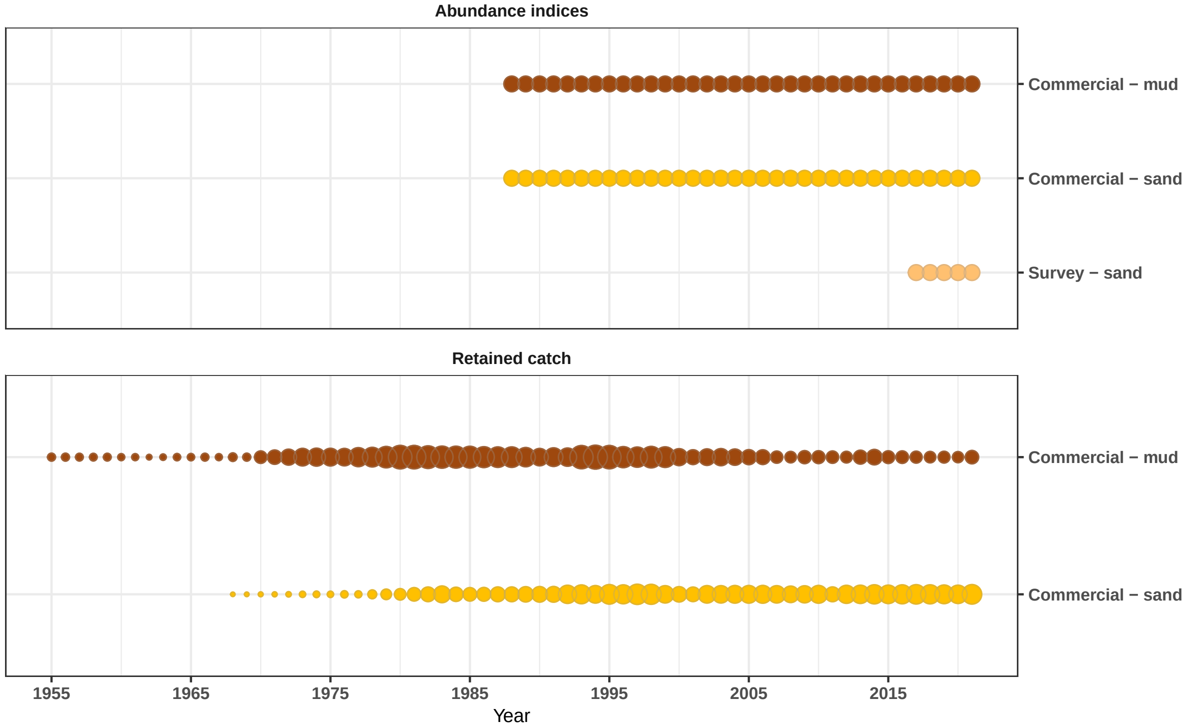

Figure 3.1: Data presence by year for each category of data type for the Moreton Bay bug stocks

3.1.2 Retained catch estimates

Total annual and monthly retained catch from commercial sector is shown in Figures 3.2–3.6. The magnitude of recreational, charter and Indigenous harvests were not considered significant for sand or mud bugs. The retained catch of sand bugs peaked in 1997 at 581 t. Over the last 5 years (2017–2021) total retained catch averaged 495 t per year. The retained catch of mud bugs peaked in 1994 at 183 t. Over the last 5 years (2017–2021) total retained catch averaged 31 t per year.

Alternative retained catch reconstructions are in Figures 3.7 and 3.8.

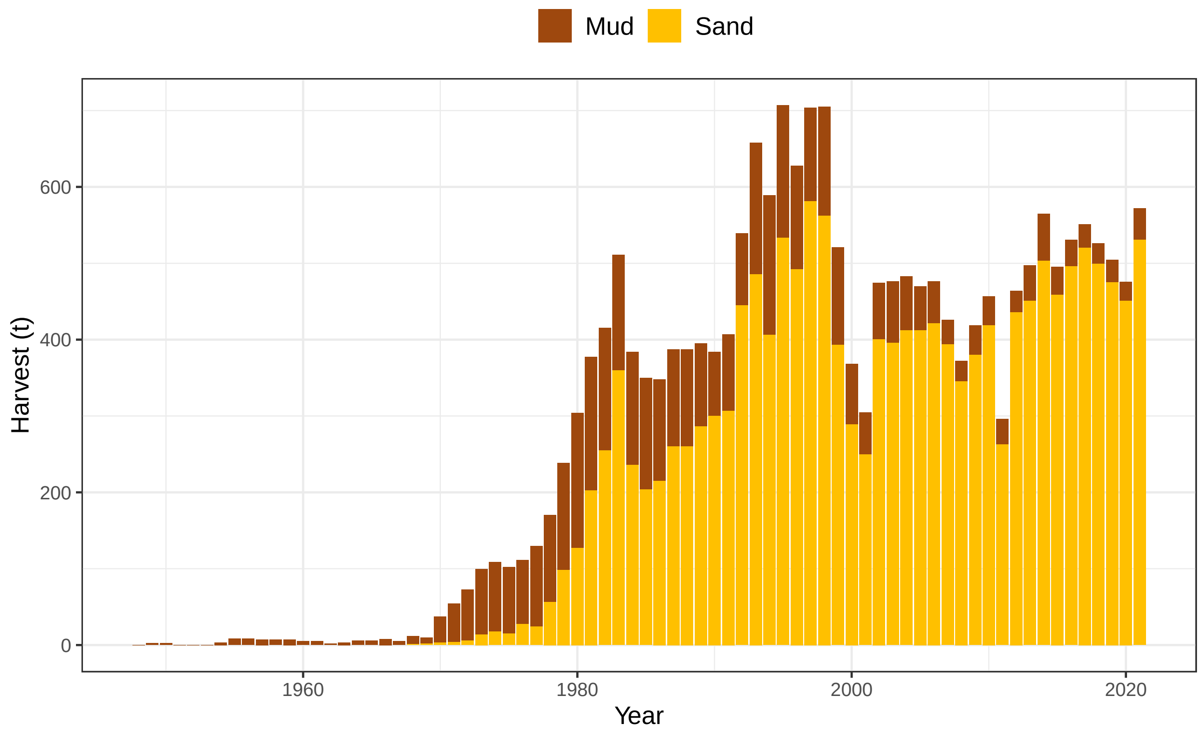

Figure 3.2: Annual estimated retained catch between 1948 and 2021 for east coast sand and mud bugs combined for the base case (project team preferred)

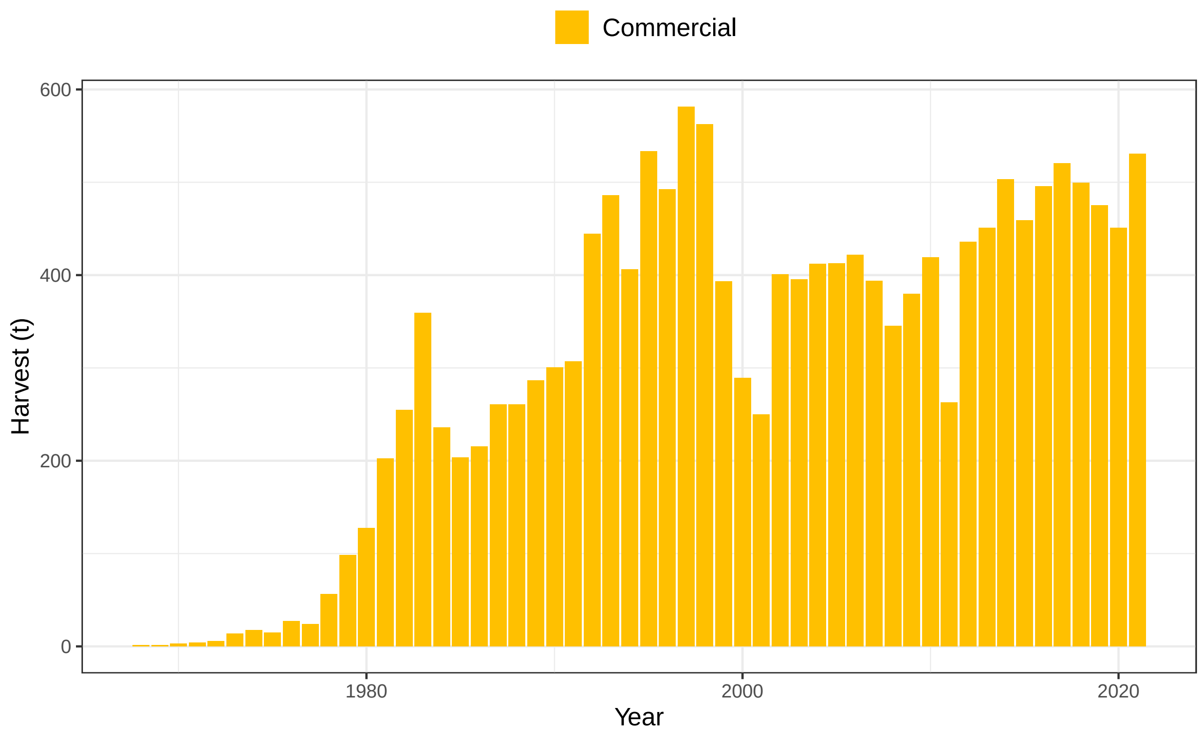

Figure 3.3: Annual estimated retained catch between 1968 and 2021 for east coast sand bugs for the base case (project team preferred)

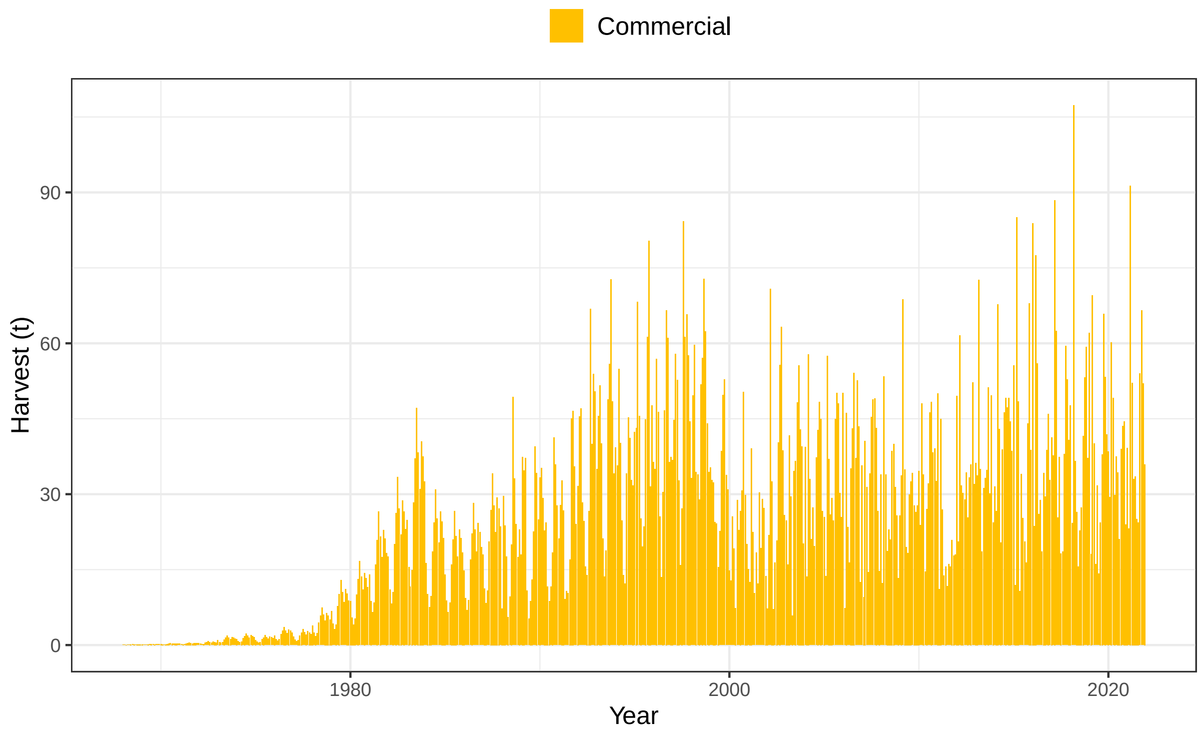

Figure 3.4: Monthly estimated retained catch between 1968 and 2021 for east coast sand bugs for the base case (project team preferred)

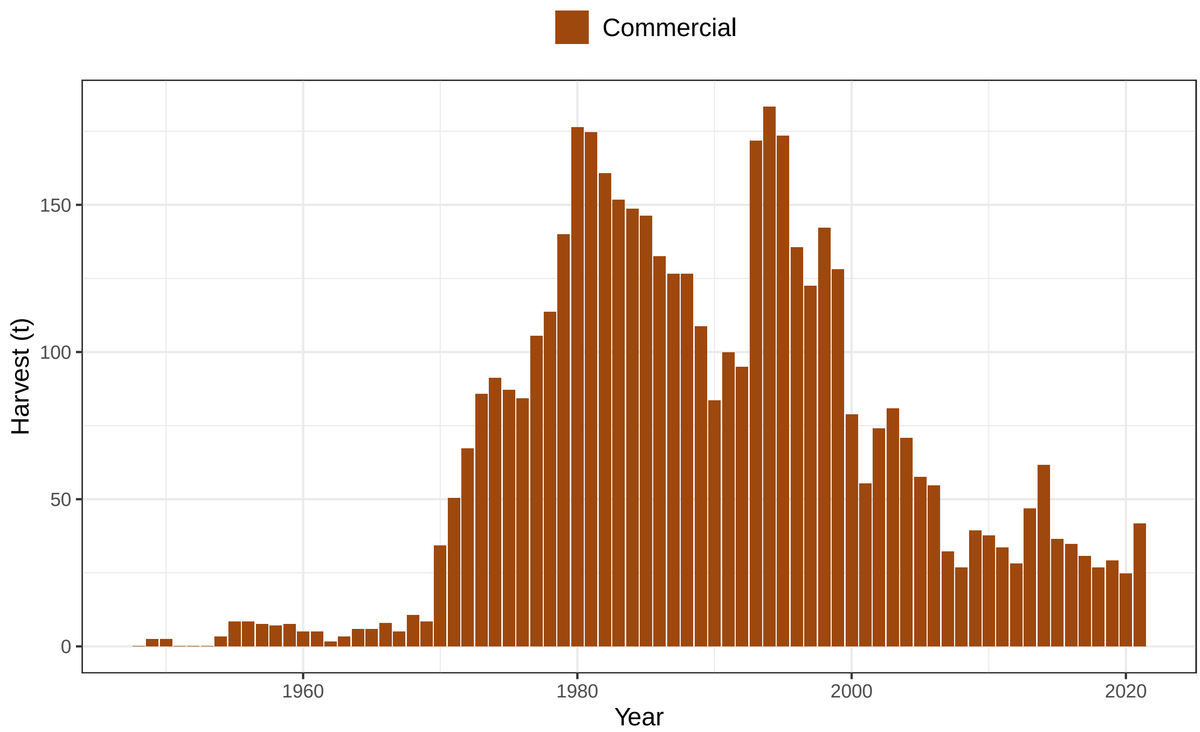

Figure 3.5: Annual estimated retained catch between 1948 and 2021 for east coast mud bugs for Scenario 1

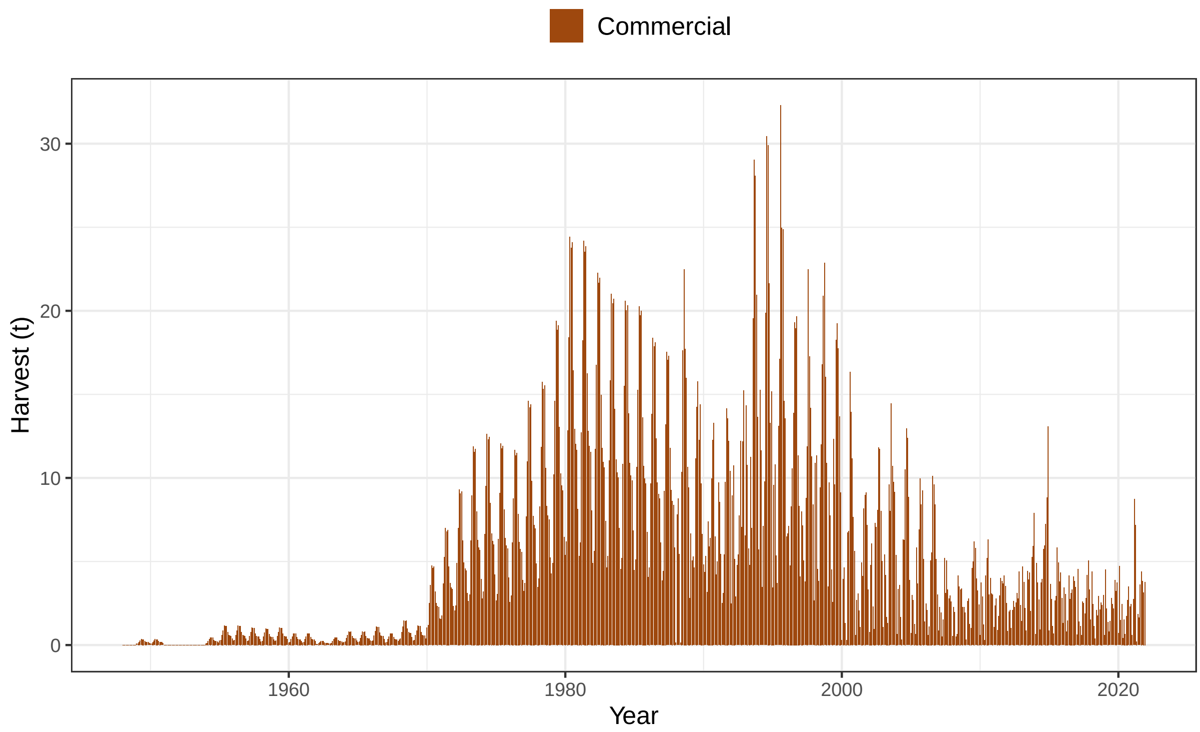

Figure 3.6: Monthly estimated retained catch between 1948 and 2021 for east coast mud bugs for Scenario 1

All four harvest sensitivity scenarios are shown in Figures 3.7 and 3.8 for sand and mud bugs, respectively.

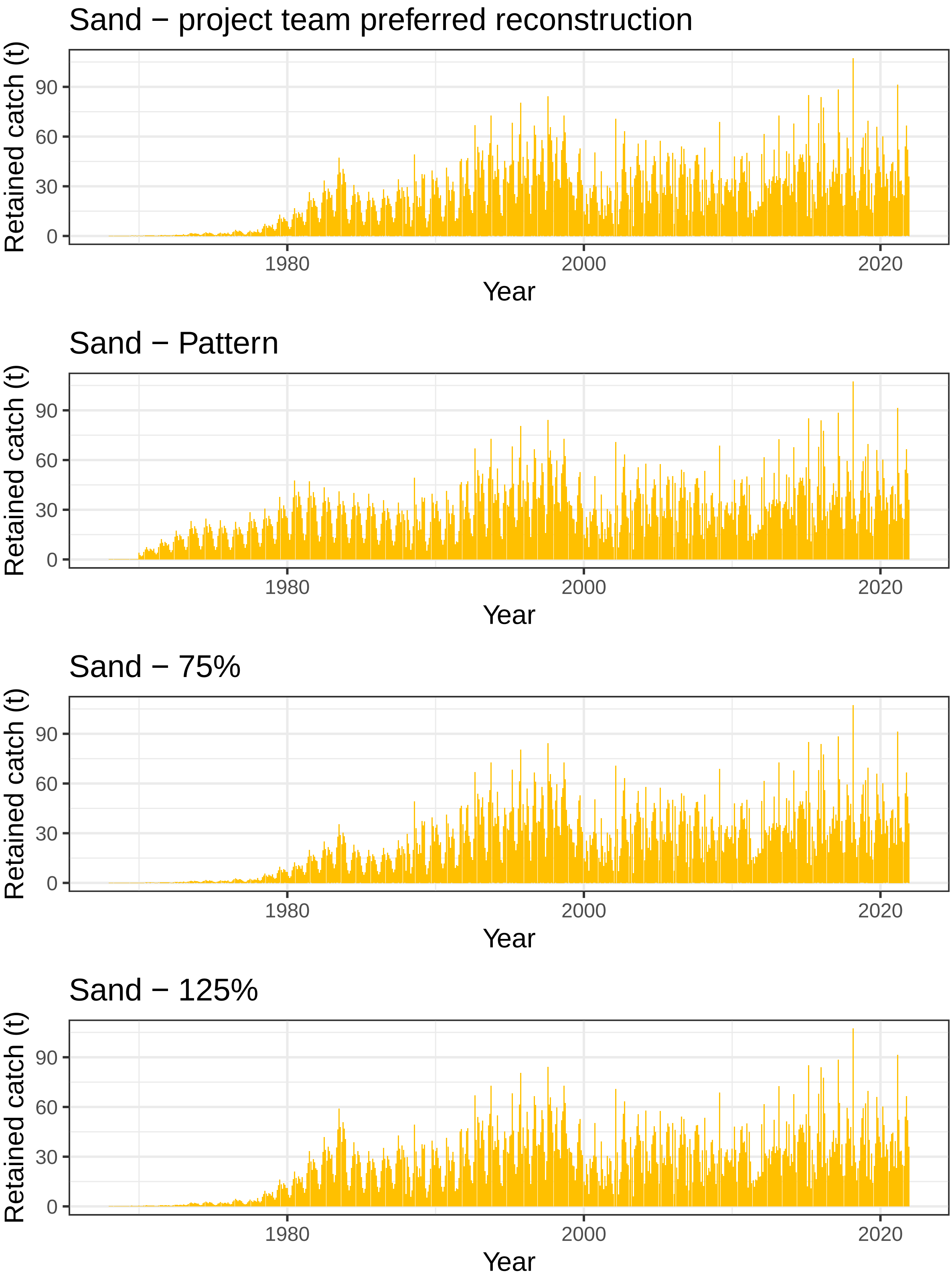

Figure 3.7: Comparison of four retained catch reconstruction scenarios

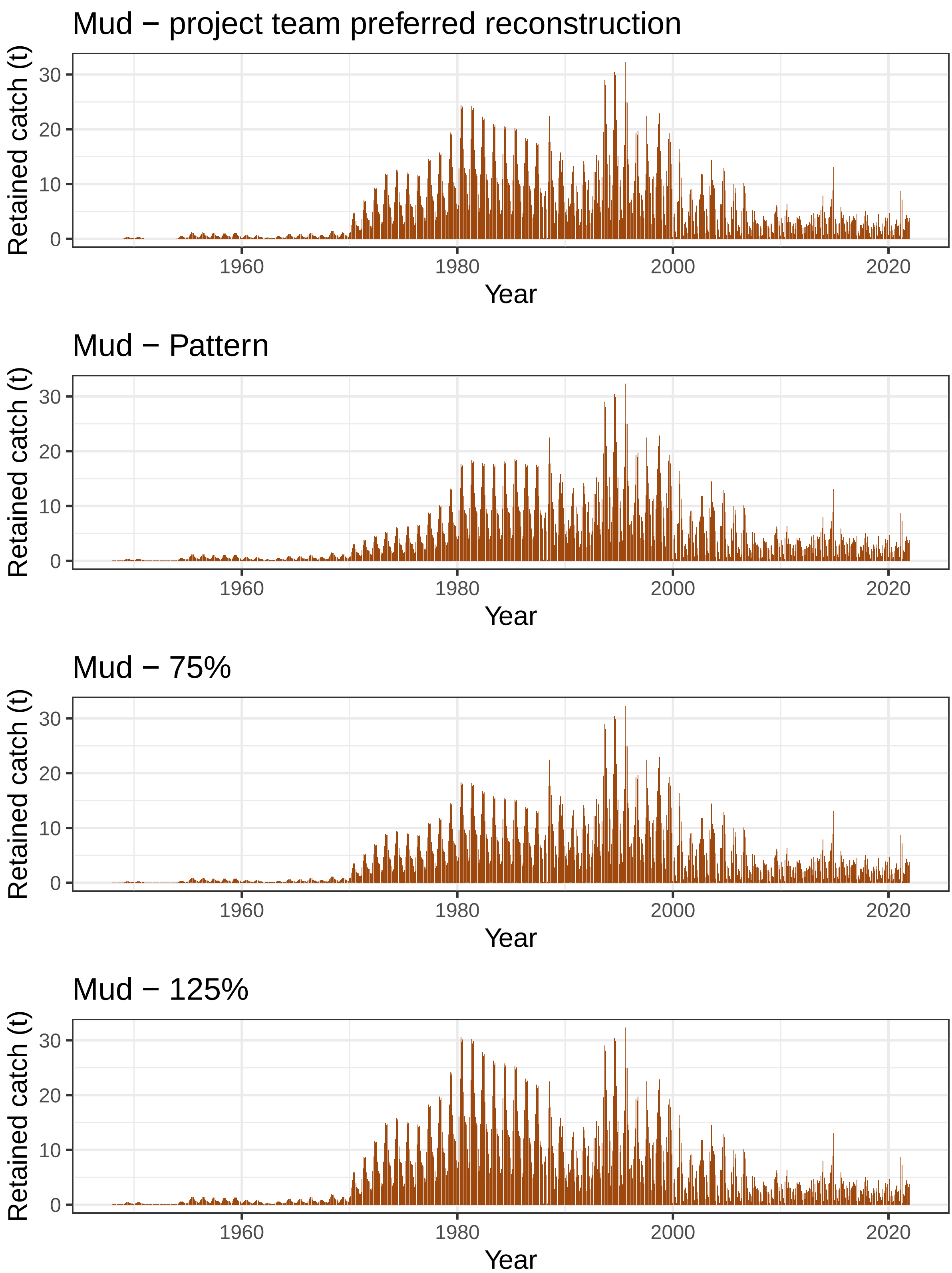

Figure 3.8: Comparison of four retained catch reconstruction scenarios

3.1.3 Standardised catch rates

At the scale of the entire ECOTF, catch rates for sand bugs showed little change through time (Figure 3.9). From 1988, sand bug catch rates generally decreased until 2000, followed by a general rise until they peaked in 2013. From 2013 to 2021, the sand bug catch rate declined again but remained above 1988 levels.

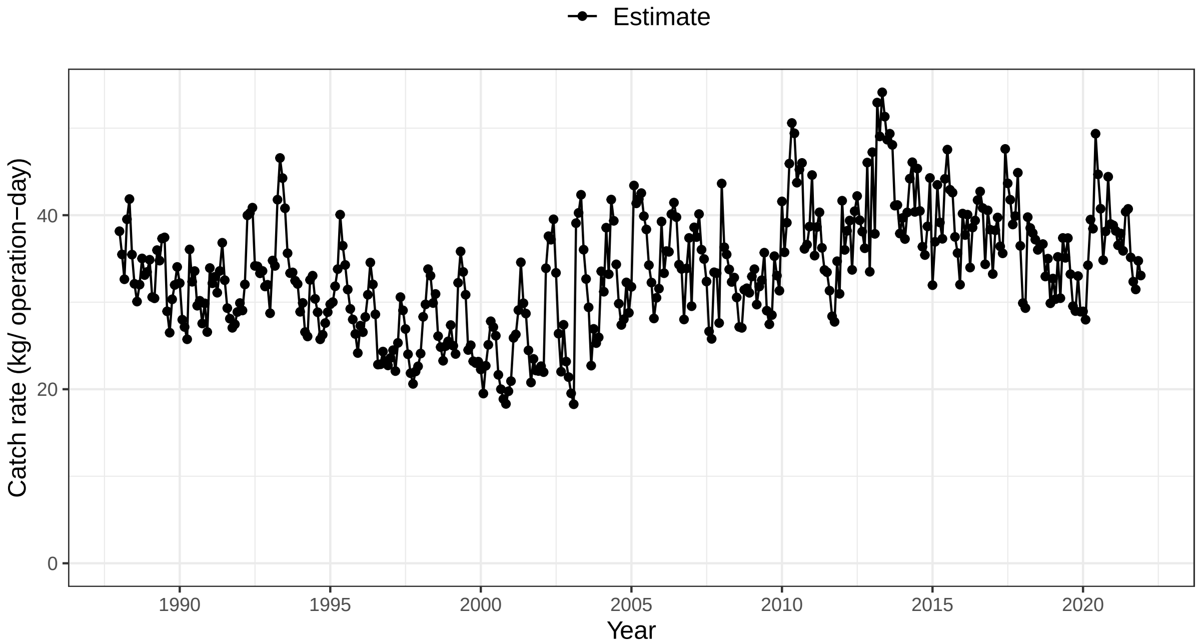

Figure 3.9: Standardised commercial catch rates for sand bugs between the years of 1988 and 2021

Catch rates for mud bugs across the entire ECOTF have remained relatively constant (Figure 3.10). The catch rate timeseries shows an increasing trend in the early 1990s with a decrease to 1996. Following 1996, the standardised catch rates indicate a slow increase for a period of 12 years (1996–2008). A stronger increasing trend occurs between 2008 and 2013, after which the catch rates decrease and stabilise at levels similar to those prior to the peak in 2013.

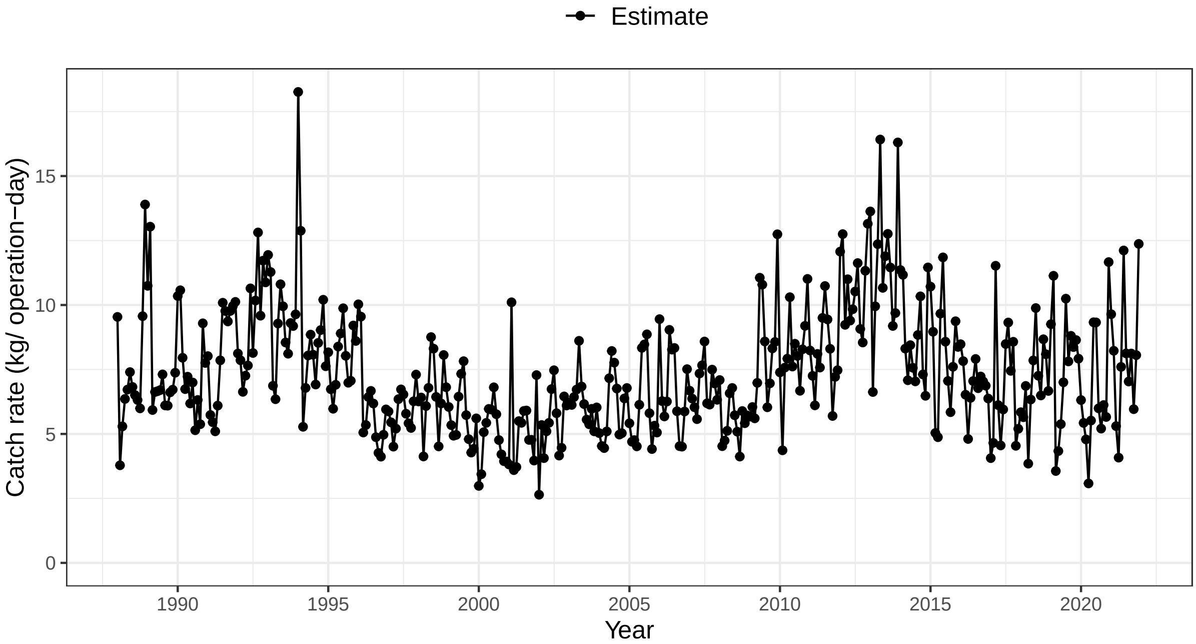

Figure 3.10: Standardised commercial catch rates for mud bugs between the years of 1988 and 2021

For sand bugs, two sources of standardised catch rates were used in modelling, commercial (Figure 3.9) and survey (Figure 3.11). For mud bugs only a single source of standardised catch rates were available for modelling (Figure 3.10).

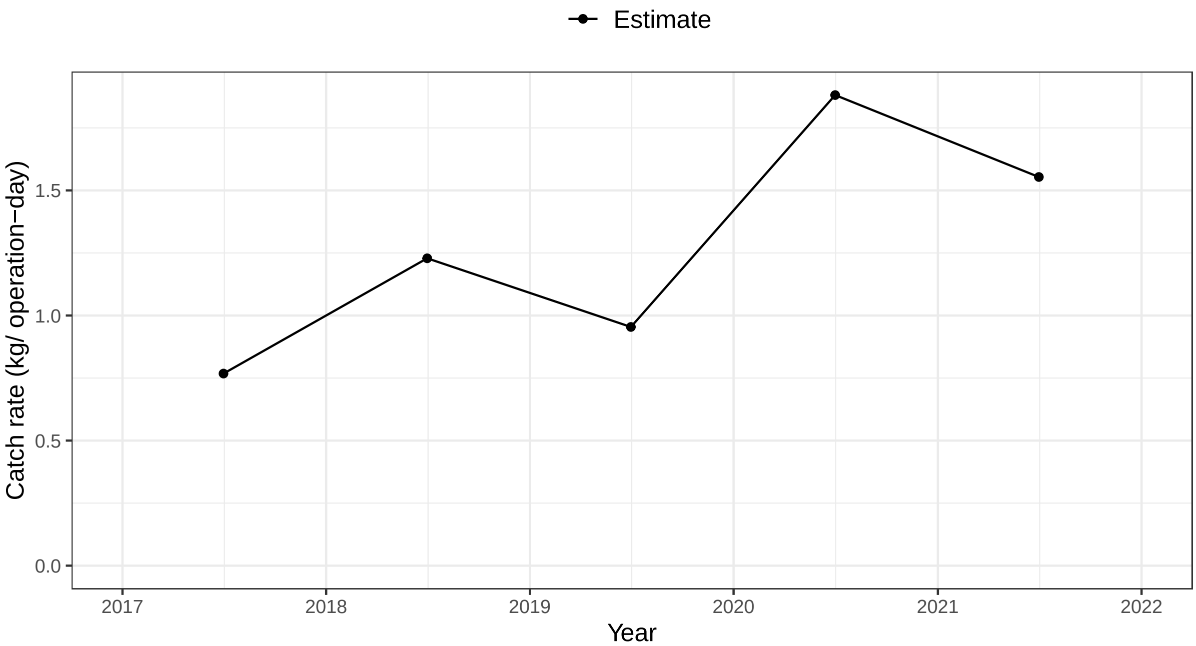

Figure 3.11: Standardised survey catch rates for sand bugs between the years of 2017 and 2021

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

3.1.4 Biological relationships

3.1.4.1 Growth curve

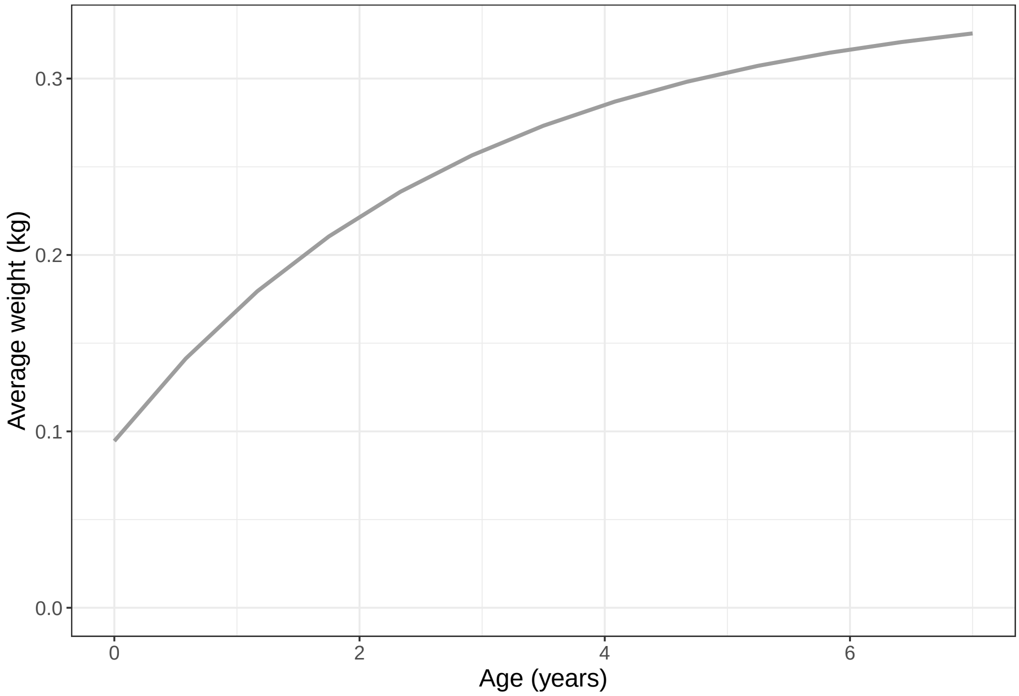

Figure 3.12: Fixed weight-at-age growth curve applied to the sand bugs model

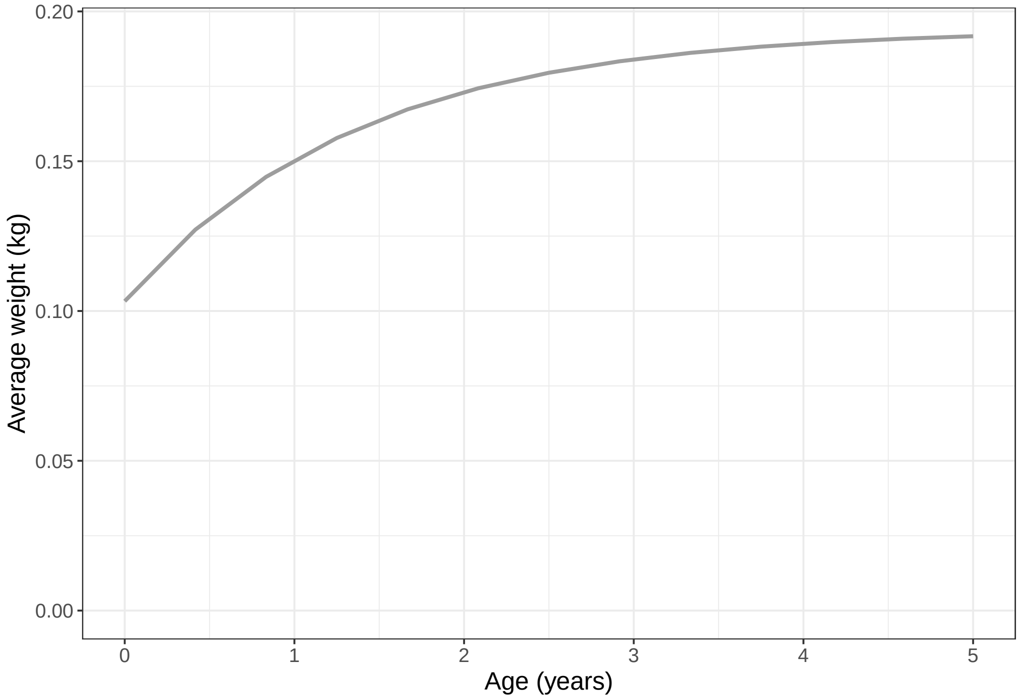

Figure 3.13: Fixed weight-at-age growth curve applied to the mud bugs model

3.1.5 Other model inputs

Other model inputs such are provided in Appendix A.2.

3.2 Model outputs

3.2.1 Model parameters

A number of parameters were estimated within the sand bug and mud bug population models (Tables 3.1 and 3.2). Table 3.1 summarises the parameter values for both MLE and MCMC estimation methods of the sand bug base case. The mud bug population modelling was unsuccessful in determining stock status and so the parameters are not presented here. The posterior distributions of estimated parameters for each of the sand bug and mud bug model scenarios can be found in Appendix B.1.

Table 3.1: Summary of parameter estimates for the project team preferred scenario for sand bugs. MLE is the parameter value found from maximum likelihood estimate results using the *optim* function. The standard deviation is associated with the maximum likelihood estimate. Median is median parameter value from MCMC chains. Median B_{2021} column is the parameter value of the trajectory resulting in median biomass in 2021.

Species	Parameter	Fixed	MLE	Standard Deviation	Median	Median B_{2021}
sand	$\ln(R_0)$	–	16.619	0.19	16.628	16.513
	ξ	–	0.892	0.731	1.047	1.374
	$log(\sigma_R^2)$	–	-4.167	0.543	-4.106	-4.257
	μ	–	-1.282	0.32	-1.462	-1.233
	κ	–	2.151	0.631	-1.857	-1.934
	q_1	–	-0.152	0.026	0.129	0.147
	q_2	–	0.176	0.031	0.037	0.033
	M	0.92	–	–	–	–
	$log(\sigma_I^2)$	-3.219	–	–	–	–

Table 3.2: Summary of derived quantities for the project team preferred scenario for sand bugs. MLE is the parameter value found from maximum likelihood estimate results using the *optim* function. The standard deviation is associated with the maximum likelihood estimate. Median is median parameter value from MCMC chains. Median B_{2021} column is the parameter value of the trajectory resulting in median biomass in 2021.

Species	Quantity	Fixed	MLE	Standard Deviation	Median	Median B_{2021}
sand	h	-	0.462	0.129	0.49	0.553
	σ_R	-	0.125	0.034	0.128	0.119
	ρ	0.971	-	-	-	-
	σ_I	0.2	-	-	-	-

All parameters in the sand bug project team preferred scenario were estimated cleanly (none hit their bounds). Final parameter gradients were small, and the hessians were positive definite implying successful convergence of MLE results. MCMC diagnostics (see Appendix B.1) also indicated a high probability of convergence for the project team preferred scenario.

3.2.2 Model fits

Good fits were achieved for the sand bug project team preferred scenario, whilst the mud bug model struggled to fit the peaks and troughs of monthly catch rate data (Figure B.86, B.90 and B.91). MCMC diagnostics (see Appendix B.1) indicate that scenarios 1, 2, 3, 4, 6, 7, 11, 12, and 13 have a high probability of convergence for sand bugs and scenarios 4, 7, 10, 11, 12 have a high probability of convergence for mud bugs. Scenario outputs of scenarios with a high probability of convergence are presented in Appendix B.2.

3.2.3 Biomass

Thirteen model scenarios were run for the sand bug stock, covering a range of modelling assumptions and sensitivity tests. The project team preferred scenario results suggest that the sand bug stock experienced a decline in the period 1968–2000 to reach around 60% of unfished biomass. The biomass has been undulating since this time with a general increasing trend, and in 2021 the stock level was estimated to be 78% (63–94% credible interval) of the unfished biomass (Figure 3.14). Relative biomass trajectories for all sensitivity scenarios are presented in Figure 3.15.

Scenario 10 was included to test the effect of seasonal catchability parameters. An explanation of this scenario is found in Section 4.2.6.

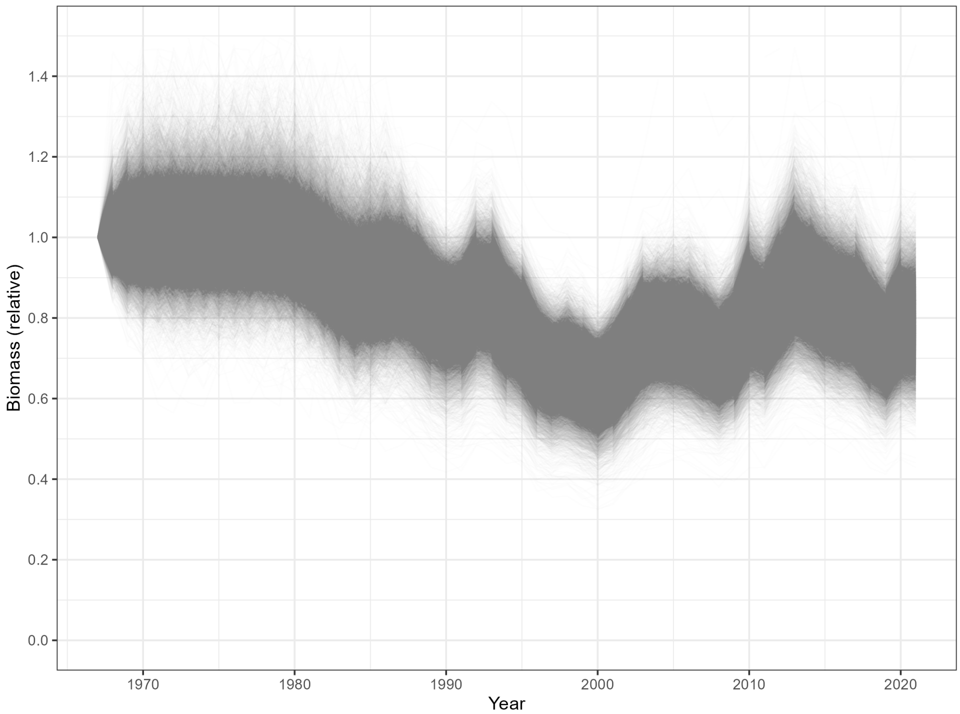

Figure 3.14: Predicted spawning stock biomass trajectory relative to unfished for sand bugs, from 1968 to 2021—grey lines represent individual MCMC samples

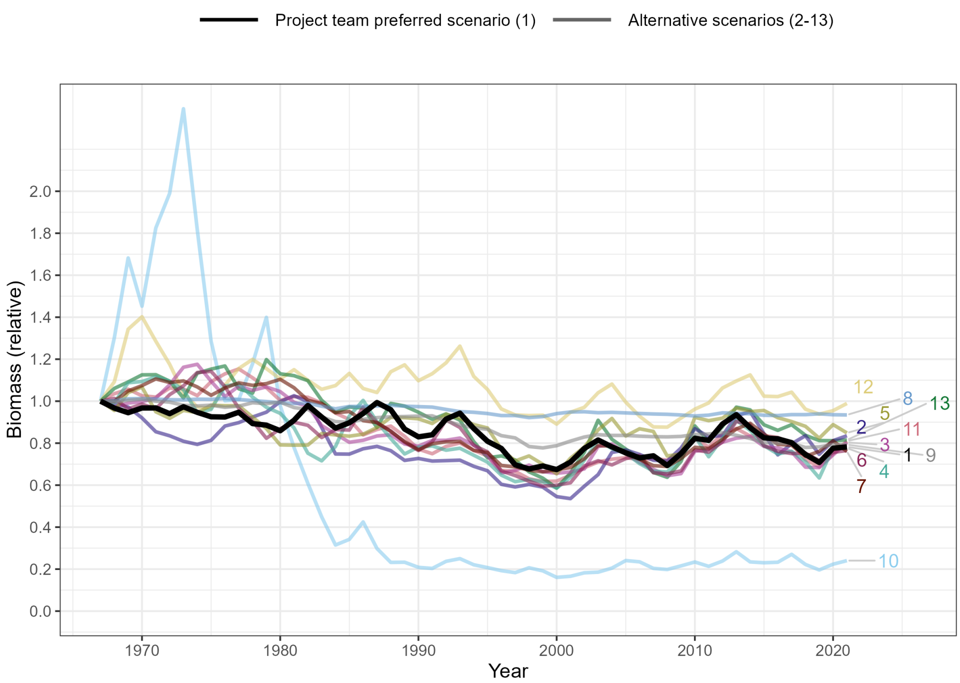

Figure 3.15: Range of predicted biomass trajectories relative to unfished for sand bugs, from 1968 to 2021, for all scenarios—the project team preferred scenario is scenario 1

Thirteen model scenarios were run for the mud bug stock, covering a range of modelling assumptions and sensitivity tests. Relative biomass trajectories for all sensitivity scenarios are presented in Figure 3.16.

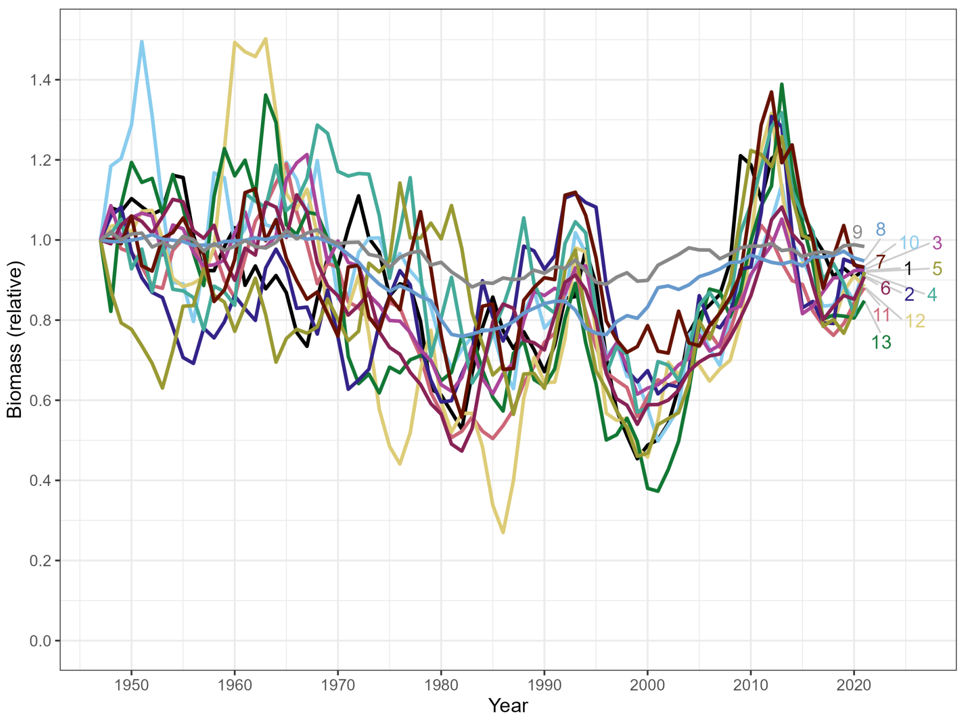

Figure 3.16: Range of predicted biomass trajectories relative to unfished for mud bugs, from 1948 to 2021, for all scenarios

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 3.3). Subject to current fishing pressure, the sand bug stock biomass is decreasing in scenario 1 (project team preferred).

Table 3.3: Stock status indicators for Moreton Bay bug stocks in 2021

Species	Indicator	Estimate
sand	Biomass (relative to unfished)	78% (63–94% credible interval)
	Biomass direction	Decreasing
	Catch	530 t
mud	Biomass (relative to unfished)	Undefined
	Biomass direction	Undefined
	Catch	42 t

Stock status indicators for all scenarios, along with model convergence and biological plausibility are presented in Tables 3.4 and 3.4).

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

Table 3.4: Summary of model outcomes for all sand bug 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
$1^{\star}_{\dagger}$	78 (63–94)	636	34	-648	TRUE	-624	TRUE	TRUE
$2^{\star}$	84 (65–102)	455	37	-617	TRUE	-612	TRUE	TRUE
$3^{\star}_{\dagger}$	80 (65–97)	641	33	-637	TRUE	-617	TRUE	TRUE
$4^{\star}_{\dagger}$	78 (63–94)	643	31	-652	TRUE	-633	TRUE	TRUE
$5_{\dagger}$	85 (64–115)	752	36	-665	FALSE	-637	TRUE	TRUE
$6^{\star}_{\dagger}$	76 (63–93)	526	35	-641	TRUE	-624	TRUE	TRUE
$7^{\star}_{\dagger}$	76 (60–93)	323	45	-645	TRUE	-627	TRUE	TRUE
8	93 (86–102)	1895	39	-375	FALSE	123	TRUE	TRUE
9	79 (61–90)	489	48	-271	FALSE	-106	TRUE	TRUE
10	24 (16–35)	342	37	-524	FALSE	-532	TRUE	FALSE
$11^{\star}$	81 (65–97)	717	36	-638	TRUE	-627	TRUE	TRUE
$12^{\star}_{\dagger}$	99 (87–115)	2618	33	-617	TRUE	-601	TRUE	TRUE
$13^{\star}$	82 (64–102)	701	36	-522	TRUE	-523	TRUE	TRUE
Ensemble	81 (63–105)	–	–	–	–	–	–	–

$\star$ models considered in the ensemble model. The ensemble model summarises all MCMC iterations across the selected scenarios.

$_{\dagger}$ models have comparable likelihoods. Lower values for the comparable likelihoods are indicative of a better fit.

$\rightarrow\leftarrow$ high probability of convergence

Table 3.5: Summary of model outcomes for all mud bug scenarios. B_{2021} % is the most likely biomass in 2021 relative to unfished in 1948 with the 95 % credible interval (CI).

Scenario	MCMC					MLE		Biological
	B_{2021} **% (CI)**	MSY **(t)**	B_{MSY} **%**	$-\ln L$	→←	$-\ln L$	→←	**Plausibility**
$1_{\ddagger}$	92 (74–122)	157	41	-298	FALSE	-259	TRUE	FALSE
2	91 (74–111)	99	44	-278	FALSE	-253	TRUE	FALSE
$3_{\ddagger}$	93 (75–116)	174	40	-336	FALSE	-254	TRUE	FALSE
$4^{\star}_{\ddagger}$	92 (74–114)	230	33	-296	TRUE	-262	TRUE	FALSE
$5_{\ddagger}$	92 (71–158)	85	45	-322	FALSE	-261	TRUE	FALSE
$6_{\ddagger}$	91 (73–117)	116	44	-319	FALSE	-260	TRUE	FALSE
$7^{\star}_{\ddagger}$	93 (75–115)	315	33	-283	TRUE	-255	TRUE	FALSE
8	95 (85–107)	277	37	-101	FALSE	111	TRUE	TRUE
9	98 (75–160)	275	56	-437	FALSE	-79	TRUE	TRUE
$10^{\star}$	93 (75–114)	247	34	-56	TRUE	-257	TRUE	FALSE
$11^{\star}$	88 (72–104)	119	43	-329	TRUE	-283	TRUE	TRUE
$12^{\star}_{\ddagger}$	88 (71–109)	94	35	-280	TRUE	-262	TRUE	FALSE
$13_{\ddagger}$	85 (63–145)	127	44	-237	FALSE	-229	TRUE	FALSE
Ensemble	91 (73–112)	–	–	–	–	–	–	–

$\star$ models considered in the ensemble model. The ensemble model summarises all MCMC iterations across the selected scenarios.

$\ddagger$ models have comparable likelihoods. Lower values for the comparable likelihoods are indicative of a better fit.

→← high probability of convergence

4 Discussion

4.1 Stock status

This assessment was the first comprehensive assessment of the Queensland east coast sand and mud bug stocks. The lack of contrast in catch rates in response to changes in catch and the lack of age data may limit the ability of the population model to separate fishing mortality from natural mortality. It is possible that the biomass and sustainable yield can not be confidently estimated until fishing has had a substantial effect.

Results from this assessment suggested that sand bug populations experienced a long period of decline followed by two shorter periods of recovery and decline. The sand bug population on the east coast experienced decline in the period from 1968 to 2000, followed by a period of stock recovery until 2003, another period of stock decline until 2008, another period of recovery until 2013 and another period of decline until 2019. From 2019 to 2021, sand bug population levels have remained steady to increasing on the east coast of Queensland. The results of the project team preferred scenario suggest that the sand bug population level at the end of 2021 was estimated to be 78% (63–94% 95% credible interval) unfished biomass.

There is insufficient confidence in the optimised mud bug model results to gain information about the mud bug stock population trajectory.

Throughout the period of logbook data (i.e., 1988–2021) multiple management changes have occurred such as vessel buy backs, the rezoning of the Great Barrier Reef (GBR) and other spatial or temporal closures (see Table 1.1. In addition to these anthropogenic influences, many other factors such as environment and food availability are likely also at play. It is important to note these potential impacts on the resulting biomass.

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. Tables 3.4 and 3.5 present the relevant model outcomes that are discussed in this section. The sand bug 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. Nine of the sand bug sensitivity scenarios also resulted in biologically plausible biomass trajectories with a high probability of convergence. Although, there were some sand bug scenarios that should be removed from consideration. The rapid biomass incline and decline exhibited by Scenario 10 is not informed by catch rate data and not biologically plausible. The MCMC chains of Scenarios 5, 8 and 9 have not shown sufficient mixing and it is likely these models have not converged. Interestingly, Scenario 5 does produce a lower negative log likelihood indicating a better fit. Nevertheless, the successful optimisation of the project team preferred scenario as well as nine sensitivity scenarios indicates that the sand bug model is robust and sufficiently informed.

In terms of mud bugs, a majority of the model scenarios did not exhibit robust parameter estimation and the biomass trajectories did not reflect the comparatively small, non-target nature of the mud bug fishery and were deemed biologically implausible. Additionally, some non-converged scenarios had better model fit than comparable scenarios. Overall, mud bugs have experienced less targeted effort from the fishery than sand bugs, leading to decreased contrast in the catch rates of mud bugs. Low contrast in mud bug catch rates likely resulted in poor model performance when compared to sand bugs. On this basis, the stock level is reported as undefined.

4.2.1 Time step

Two options for the time step used in the model were considered: annual and monthly. It is common for population models to use an annual time step for long-lived species such as trout (Campbell et al. 2019) and a monthly time step for short-lived species such as prawns (Dichmont et al. 2003a). In DDUST, the annual model is more parsimonious, with a reduced number of parameters and simpler recruitment, spawning and catchability methods. The annual model injects a pulse of recruitment at the start of the year and assumes a constant catchability throughout the year. Monthly indices of abundance are weighted and averaged to produce annual indices. Monthly retained catch is summed to produce annual harvest. The monthly model, on the other hand, includes functionality for a seasonal recruitment pattern, seasonal spawning pattern and seasonal catchability pattern. The functional forms of these patterns are described in Appendix E. In the monthly model, the biomass trajectory is informed by twelve index of abundance data points and twelve harvest data points every year. The monthly model was preferred by the project team for both Moreton Bay bug species with a sensitivity test (Scenario 9) for an annual time step.

The sand bug and mud bug annual scenarios (Scenario 9) produced a smoother biomass trajectory as recruitment deviations are not influenced by variance in monthly catch rates. The final biomass from sand bug Scenario 9 was not significantly different to the project team preferred scenario. The final biomass from mud bug Scenario 9 was the highest median biomass estimate.

4.2.2 Split vs continuous catch rate

Two scenarios were considered to attempt to model the effects of the 2004 rezoning of the GBR. During 2004, a considerable area of the GBRMP was closed to trawl fishing. Grech et al. (2011) reported changes would decrease the trawl footprint of the ECOTF by approximately 4.8%. Hand (2003) reported changes would decrease the trawl footprint by approximately 6% for the ECOTF. DDUST modelling attempted to account for such changes in the area available to trawl effort by using catchability. In stock assessment, an index of abundance (i.e., commercial catch rate) is combined with an estimate of catchability (i.e., what proportion of the true abundance are caught by fishing gears) to explain the total abundance of sand or mud bugs. By splitting the standardised index of abundance during July 2004, separate catchabilities were estimated prior to (i.e., 1988 to June 2004) and after the rezoning (i.e., July 2004 to 2021). This process allowed the model to internally estimate the effects of the Great Barrier Reef rezoning and formed the basis of the two scenarios.

Splitting catch rates was incorporated as a modelling option allowing the model to estimate how catchability had changed from areas lost to trawling as a result of each closure. The population model assumes a dynamic pool which means recruitment and movement of animals is equally distributed spatially. However, this assumption may be violated for many reasons including habitat preferences and complex larval dispersal mechanisms.

For sand bugs, catchability was estimated by the model to be higher after the rezoning of the GBR for split catch rate models. The exact cause of higher catchability after 2004 was unable to be determined.

A possible explanation is that sand bugs were generally not targeted prior to 2004, but targeting began sometime around 2004 and is maintained today. Alternatively, it is possible that the targeting term included in the catch rate standardisation may not have been fully standardised for different targeting behaviour of sand bugs among vessels.

Lower catchability after the rezoning was estimated by the model for mud bugs in split catch rate scenarios.

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.

4.2.3 Retained catch

Four different scenarios pertaining to the historical retained catch data were run. For sand bugs, the project team preferred historical retained catch reconstruction used the Htrawl voluntary dataset. These data were converted to kilograms per record which then informed the trend used to hindcast the 1988 logbook data back to 1968. The Htrawl data contains around 1000 voluntary sand bug records and only 60 voluntary mud bug records. For this reason, a different method was used to reconstruct the mud bugs historical retained catch. For mud bugs, the number of boats operating in the fishery was shown to have a strong correlation with the total catch. The proportional change (trend) in number of licences operating was used to hindcast mud bug catch from 1988 to 1970. To match with the catch data which already exists prior to 1970 (data from Jones (1984) and FishBoard), the data has been tapered off in the last five years (1970–1975) to match up with the low catches prior to 1970 for both species. Another justification for the tapering off of the data is the development of radar and use of dan buoys. Due to the uncertainty around historical Moreton Bay bug retained catch, the project team chose three alternative scenarios. One to test the model's sensitivity to the pattern of the historical retained catch, and two to test the model's sensitivity to the magnitude of the historical retained catch. The sand bug pattern scenario uses the same method as the mud bug project team preferred reconstruction. The mud bug pattern scenario uses a linear tapering over the years 1970–1987 instead of just 1970–1975. The magnitude tests reduce or increase the project team preferred historical retained catch reconstruction by 25%. Due to numerous species name and reporting changes, the most appropriate amount of adjustment to the available data from 1948 to 1988 remains a notable source of uncertainty.

Scenario 5, 6 and 7 test the pattern, 75% and 125% reconstructions respectively. For sand bugs, scenario 5 produced a better model fit than the project team preferred reconstruction despite non-convergence. However, all four scenarios (1, 5, 6 and 7) result in similar median biomass estimates. For mud bugs, Scenario 5 and 6 produce better model fits despite non-convergence. However, all four scenarios (1, 5, 6 and 7) result in similar median biomass estimates.

4.2.4 Natural mortality

Three values were used to test the sensitivity of models to natural mortality. Of these three values, estimates from the literature formed the central basis (i.e., medium level). The two additional values tested were −0.2 that of the medium (i.e., lower level) and +0.2 that of the medium (i.e., higher level). Scenarios testing the sensitivity of model outputs showed little influence to different levels (i.e., low, medium and high) of natural mortality for both sand and mud bugs.

Scenario 3 and 4 test sensitivity to low and high natural mortality, respectively. For sand bugs, Scenario 4 produced a better model fit as indicated by the lower negative log likelihood value but showed an identical median biomass estimate and uncertainty. For mud bugs, Scenario 3 produced a better model fit as indicated by the lower negative log likelihood value but all three scenarios (1, 3 and 4) showed similar biomass estimates and uncertainty.

4.2.5 Standard error of indices of abundance

The indices of abundance produced by the catch rate standardisation error were informed by approximately 850 000 records of sand bug catch and 310 000 records of mud bug catch. The catch rate standardisation model used a linear regression model to predict the catch per boat day (catch rate) while accounting for different fishing situations such as year, month, region, and authority chain number. The full explanation of the standardisation process can be found in Section 2.4. Due to the large number of data used in the model, the statistical standard error of the catch rate is very small (<0.1). The population model uses the abundance indices as data. Thus, any additional process error (model selection) or observation error needs to be included with the indices when given to the population model. For this reason, the standard error of the abundance indices was fixed at 0.2 for sand bugs and 0.5 for mud bugs. Other values were also tested as sensitivity scenarios and presented as Scenario 8 for both species. By increasing the standard error of the indices of abundance, the model is not forced to use large recruitment deviations to create a close fit. Therefore, the variance of the recruitment deviations, σ_R, will be much smaller and the estimated stock-recruitment trend is prioritised as opposed to year-to-year recruitment to match unexpectedly high/low catch rates. This may result in a model that is less likely to over fit the data and produce an overly dynamic stock-size trajectory.

For both species, Scenario 8 did not show convergence when optimised with MCMC but the biomass trajectories are plausible and may have succeeded with more iterations. It is likely that the additional error around the catch rate data complicated the parameter space and increased the difficulty of diagnosing convergence.

4.2.6 Seasonal catchability

The seasonal catchability parameters allowed the model to vary the relationship between the indices of abundance and biomass throughout the year. The seasonal catchability equation is a modified version of the seasonal catchability equation published in Courtney et al. (2014a) and is described in E.

A sensitivity scenario (Scenario 10 for both species) was included where the seasonal catchability parameters q_1 and q_2 were fixed to values that forced the model fit to be as extreme as the high peaks and low pits of the monthly catch rate timeseries data. For sand bugs, the variance of the recruitment deviations, σ_R, also needed to be increased to achieve the fits.

For sand bug scenario 10, the biomass dramatically increases and dramatically drops before logbooks started which is not supported by any data. Additionally, the MCMC optimisation diagnostics suggest non-convergence. Therefore, this model has not successfully converged on a reasonable solution and is removed from the set of robust scenarios for consideration.

For mud bug scenario 10, the model fit exaggerates the monthly pattern in catch rates (see Figure B.87). However, the MCMC model diagnostics suggest convergence so was added to the set of scenarios for consideration. It is hypothesised that the model captured the mud bug population better in this sensitivity scenario because the monthly variation is only approximately 5 kg per boat-day whereas sand bug variation was closer to 10 kg per boat-day.

4.2.7 Targeting

Targeting played two important roles in the current assessment. Targeting was firstly implemented to standardise for an increase in targeting among years for sand bugs. That is, up until approximately the 2000s, sand bugs were not targeted by fishers as they are today. The same is not true for mud bugs so the targeting term was removed from the mud bug catch rate standardisation process. During the final project team meeting, industry members raised concerns regarding illogical patterns (double peak) in seasonal (i.e., monthly) catchability of mud bugs (see Figure B.91). Industry proposed that the targeting of other species such as tiger or endeavour prawns was likely having a flow on effect to byproduct constituents within the catch, such as mud bugs. For example, large captures of tiger and endeavour prawns occur during March, April and May in the northern trawl region, whilst large catches of endeavour prawns and scallops occur during the middle of the year in the central trawl region. It was hypothesized that re-adding the targeting term to the mud bug standardisation process would account for different levels of targeting among months (i.e., within year variation). The addition of targeting corrected the seasonal catchability rate pattern for mud bugs and is shown as an extra modelling scenario (Scenario 11).

In Figure 3.16, Scenario 11 shows a trend consistent with other scenarios and has a high probability of convergence when optimised with MCMC.

4.2.8 Alternate growth curves

Two sources of information on growth were available for the present assessment: Jones (1988) and Courtney (1997). The main difference is the larger estimates of mean maximum asymptotic size (L_∞) reported by Jones (1988). Initially growth was based on the more recent study of Courtney (1997). Concern was raised that the L_{inf} estimates from Courtney (1997) were not reflective of the size sand and mud bugs could achieve. The additional model runs with growth inputs from Jones (1988) are shown as an extra modelling scenario (Scenario 12).

When examining length composition data in Figures F.10, F.11, F.12, F.13, F.14 and F.15, few individuals exceed 100 mm carapace length in length frequency data from scientific trawls. For example, a fishery-independent survey of Moreton Bay bugs off Townsville found that sizes, measured in carapace length, ranged from 23–85 mm for mud bugs and 24–95 mm for sand bugs (McMillan 2022, unpublished data).

Scenario 12 showed an increased biomass for sand bugs when compared to growth curves input from Courtney (1997). Scenario 12 produced the most variable biomass trajectory for mud bugs but little difference in final biomass ratio. The growth curve sensitivity scenario for both species showed a high probability of convergence.

4.2.9 Target only catch rates

Upon request from representatives on the project team, sand bugs Scenario 13 presents the results from using only target records in the catch rate standardisation. As outlined in Section 2.4.3, target records are identified when the revenue of the bug catch is two or more times greater than the revenue from the next most profitable species in the catch record. This method relies on the catch (in kilograms) to identify target records, so limiting the catch rates to use target records means using records with large catch only. This can lead to a phenomenon called *hyperstability*. Hyperstability is often present in fisheries with aggregating populations. Even if the biomass is decreasing, the records with the species present contain a large catch because the fish school. A similar problem may occur when filtering data to only use records with large catch. The model will receive information about instances where the fishers were targeting bugs but could not find many. Nevertheless, this scenario has been included as a sensitivity test for sand bugs.

Scenario 13 for sand bugs performed very similar to the project team preferred Scenario 1 with a similar biomass trajectory, high probability of convergence and similar final biomass.

4.2.10 Residual filtering

Upon request from representatives on the project team, mud bugs Scenario 13 presents the results with catch rates filtered by excluding data with deviance residuals greater than 1.5 and then re-fitting the generalised linear model. The resulting standardised catch rates and the model fit are shown in Figure B.87, Scenario 13. Concern was raised by industry that high deviance residuals may have indicated the presence of a more efficient fleet (i.e., higher catch rate) for mud bugs. The process of excluding data with high deviance residuals removed 20 108 records from a total of 295 277 used in the catch rate analysis for mud bugs.

Analysis of the records with high deviance residuals indicated no regional, monthly, or yearly bias because the proportion of high-residual records coming from each category is similar to the proportion from all the records. Similarly, the co-caught species between records with large residuals and the rest of the data showed no pattern here dissimilar to the patterns existing in all the data. Therefore, based on regional, temporal and co-caught species comparisons, it is unlikely that the high residuals are due to a non-random fishing effect that could be extracted using available data. Additionally, species such as tiger and endeavour prawns constituted the mud bug data with high deviance residuals, likely indicating these records are true mud bug catches and not misidentified sand bug catches.

Scenario 13 for mud bugs performed very similar to other scenarios with a similar biomass trajectory and final biomass but it has likely not converged during MCMC optimisation.

4.2.11 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 Moreton Bay bugs. 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 F.

4.3 Unmodelled influences

There are a number of possible drivers of the sand and mud bug populations that have not been directly modelled, but should be taken into consideration when interpreting model outputs and considering future assessments and management arrangements. These include sex, length, selectivity, and environmental/climatic influences. These four key influences are discussed below:

- **Sex-specific growth:** Female bugs grow significantly larger than males for both sand and mud bugs (Courtney 1997). In the current DDUST model used for this assessment, both sand and mud bug growth was modelled using a combined-sex growth equation. Future assessments should aim to model sex-specific growth to more accurately represent the biology of sand and mud bugs.
- **Selectivity:** Another result of sex-specific growth for sand and mud bugs are differences in selectivity and thus, vulnerability to the fishery. As females reach larger sizes than males, females are exposed to fishing at a younger age than males. Further, sand bugs are targeted using two different trawl gears, prawn and scallop gear. Prawn trawl gear is constructed with smaller net mesh size (2.5 inch net mesh size) when compared to scallop trawl gear (4 inch net mesh size). The use of prawn trawl or scallop trawl gear likely varies spatially and temporally throughout the fishery, again leading to differences in selectivity. 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:** Multiple sources of fishery independent length data are available for sand and mud bugs. A time series of fishery independent length frequency data (1998–2006 and 2017–2022) from the DAF FM scallop survey is available for both sand and mud bug populations on the southern portion of the fishery. An additional source of sand and mud bug length frequency data is available from a second fishery independent trawl survey in 2021 as part of a FRDC project conducted in the Townsville region. Length data cannot be incorporated into current DDUST modelling, however. Future efforts should focus on achieving a plausible outcome from an analysis that can incorporate length frequency data such as Stock Synthesis.
- **Discards:** Discards were not modelled in the current assessment. Future assessments should aim to incorporate an estimate of discards or be capable of modelling selectivity to infer discards.
- **Environmental/climatic influences:** The environmental influences on sand and mud bug populations dynamics (i.e., recruitment, survival) are unknown and therefore were not modelled in the current assessment. However, a possible link between recruitment and the Southern Oscillation Index (SOI) has been identified as a potential research area. Environmental drivers (i.e., SOI) may be additional drivers of sand and mud bug abundance through time. Future research is required to understand any links between population dynamics of sand and mud bugs and the environment.

4.4 Recommendations

4.4.1 Research and monitoring

Research and monitoring recommendations for sand and mud bugs should focus on prioritising the reduction in model uncertainty and the rectification of caveats. These recommendations are given below:

- **Selectivity:** DDUST uses knife-edged selectivity which may not be appropriate for the Moreton Bay bug populations. It is more likely that the selectivity for sand and mud bugs has a logistic form. For sand bugs, two main trawl gear types are used, prawn and scallop gear. Scallop gear is typically constructed of a larger mesh of approximately 4 inches (100 mm) whilst prawn gear has a mesh size of approximately 2.5 inches (62.5 mm). Future assessments should aim to incorporate different gear selectivity in modelling.
- **Fishery independent sampling:** Fishery independent data (DAF FM scallop surveys and FRDC survey) provided a key source of information to DDUST for modelling. After the rezoning of the Great Barrier Reef in 2004, some proportion of the stock is likely protected in areas closed to fishing. Although fishery-dependent data collection continues, for many assessments and species data can no longer be obtained from areas closed to fishing. Priority should be placed on the

continuation of the DAF FM scallop survey to provide fishery-independent data from areas both open and closed to fishing. Further stock assessment benefit could be added to the DAF FM survey by examining the number of recruits for other commercially important species (i.e., *Lutjanus sebae, Lutjanus malabaricus, Chrysophrys auratus, Glaucosoma scapulare*) to form an index of recruitment.

- **Catchability:** Project team preferred catch rates for sand and mud bugs allowed catchability to be split into two time periods (i.e., pre- and post-rezoning) with catchability estimated separately before and after the rezoning of the Great Barrier Reef. Splitting catch rates pre- and post-rezoning was incorporated as a modelling option allowing the model to estimate how catchability had likely changed due to areas closed to trawling in the Great Barrier Reef in July 2004. For mud bugs, catchability was lower after the rezoning in 2004, likely due to lost trawlable area. For sand bugs, catchability increased after rezoning in 2004 despite lost trawling area. Future research should aim to validate if catchability has increased after rezoning or if other factors are at play (i.e., increased targeting, less efficient fishers leaving the fishery) as discussed in Section 4.2.2. It is also possible that the catchability term is consuming leftover effects from sand bug targeting. Rather than the sand bugs having a higher catchability after 2004, the model may be trying to further account for increased targeting behavior.
- **Fishing power:** Future work should aim to better quantify advances in trawl gear efficiencies. For example, the transition to trawl nets with 'lead ahead'. Historically, trawl nets tended to have equal headline (i.e., top leading edge of the net) and footline (i.e., bottom leading edge of the net) lengths, causing the headline to be directly above the footline when trawled. However, trawl nets set up with lead ahead have a shorter headline, causing the headline to act as a 'ceiling' as it travels in front of the footline. This ceiling likely decreases the ability of Moreton Bay bugs to swim over the headline and avoid capture, improving trawl efficiency when targeting Moreton Bay bugs. Additionally, future work should also better quantify the effects of increased fishing power through new technologies such as modern charting and mapping technologies. Trawl fishing is heavily dependent on seabed characteristics with different species preferencing different habitats. Multiple sources of bathymetric mapping are now available on charting devices, in addition to the capability for fishers to create their own personalised maps at finer scales specific to their area. This has likely improved fishers' ability to better understand and target specific species.
- **Effective hull units:** A recommendation from the current assessment process was to investigate the usefulness of standardised hull units. Effective hull units are a management implementation to provide a means of measuring the size of each vessel encompassing the length, beam and depth of the vessel. The fleet profile of standardised hull units may provide some benefit when applied to a fishing power. For example, as a general trend through time, the number of boats in the fleet has decreased but simultaneously smaller boats have been replaced by larger boats. In other words, the effective hull units per licence has increased through time as boat size increased. The metric of standardised hull units may provide potential benefits to other aspects of the assessment when investigated.
- **Natural mortality:** No direct estimate of natural mortality was available for mud bugs in the current assessment. Courtney (1997) reported a direct estimate of annual instantaneous natural mortality at a rate of 0.92 per year for male and female sand bugs through a field tagging study. No such tagging study has been conducted for mud bugs. Rather, the present study relies on an estimate of natural mortality inferred from an equation based on maximum age and temperature from Pauly (1980). Courtney (1997) reported an annual instantaneous natural mortality at a rate of 1.29 and 1.23 per year for male and female mud bugs, respectively. Indirect estimates of natural mortality such as those derived from Pauly (1980) have been shown to be inaccurate (Newman et al. 1996;

Pascual et al. 1993). The validity of natural mortality estimates used for mud bugs in the current assessment would be greatly improved with a field tagging study.

- **Environmental/climate change:** Much research has focused on the effects of climate change on coral reefs (see Hughes et al. (2017)). Little is known how climate change may impact upon inter-reefal areas where sand and mud bugs inhabit, however. Additionally, as sand and mud bugs are crustaceans with a calcareous exoskeleton, ocean acidification may negatively impact upon biological processes (i.e., settlement, growth and molting) and ultimately survival (see Gravinese et al. (2020), Whiteley (2011), and Liu et al. (2022)). Future research should aim to quantify the effects of ocean acidification on sand and mud bugs.
- **Economic data:** A large improvement to the current assessment was the specification of targeting used to standardise commercial catch rates. Thanks to industry involvement, a time series of market value data (price per kilogram) was constructed back as far as 1998 for most trawl species. A species-specific time series of market value data enables the calculation of Moreton Bay bug revenue relative to the rest of the catch, per night. This relative value of Moreton Bay bug revenue was then used to infer if Moreton Bay bugs were targeted or not. However, this time series of market value data needs to be consistently updated to enable the continued calculation of targeting for the next assessment.
- **Age data:** Determining age data from crustaceans such as crabs, prawns, and bugs has proven challenging given crustaceans must molt to grow (Hartnoll 1978; Hartnoll 2001). Recent developments in the field of DNA methylation may in the future provide a means of age determination for crustaceans (see Fairfield et al. 2021). Accurate age data would benefit future stock assessment modelling potentially allowing the use of Stock Synthesis.

4.4.2 Assessment

- **Stock Synthesis modelling:** Future assessments should continue to experiment with Stock Synthesis to assess Moreton Bay bugs, particularly sand bugs. Stock Synthesis has the ability to incorporate length- and age-based data (age data for Moreton Bay bugs is not currently available however). The incorporation of length-based data allows a number of processes to be estimated including selectivity, discarding, minimum legal size and sex-specific growth. 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 sand and mud bug population dynamics can also be modelled using Stock Synthesis.
- **Spatial modelling:** There has been little work done to understand sand and mud bug ecology in Queensland including movement and connectivity of adults and juveniles between management regions and aggregation sites. Future research on the movement rates and patterns of sand and mud bugs may allow the development of a spatial structure to model areas at a finer scale within the fishery.
- **Mud bug targeting:** The targeting term was not utilised when standardising mud bug commercial catch rates. Investigations from DDUST modelling suggest that while targeting of mud bugs may not have changed among years, differences in catchability resulting from targeted effort from other fisheries such as tiger prawns can occur. Future assessments should include a targeting term in mud bug standardisations. One such way to standardise the catch rates for targeted mud bug effort may be to split the non-target category of mud bug records into two fleets. One fleet would be for records that targeted tiger prawns and one for other targeted species. Fishing behaviour changes between target species, therefore catchability for mud bugs may also change. The model would then assign a different catchability to the two by-product fleets.

- **Industry participation in project team meetings:** Industry member involvement in the current assessment has greatly improved the capability, validity, and robustness of the assessment. Future assessments should aim to continue to engage with industry members to further enhance assessments and build collaboration between industry and government.

4.5 Conclusions

This assessment was commissioned to establish the status of Queensland's Moreton Bay bug stocks and inform the management of the Queensland East Coast Otter Trawl Fishery. The project team preferred model scenario suggested current biomass (compared to unfished levels) for the sand bug stock is around 78%, with a range of estimates of 63-94% produced by the full suite of robust scenarios. The mud bug stock assessment does not provide a biomass estimate due to the non-target nature of the fishery and insufficient data being available to compensate for this.

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Appendix A Model inputs

A.1 Catch rate diagnostics

A.1.1 Term influence

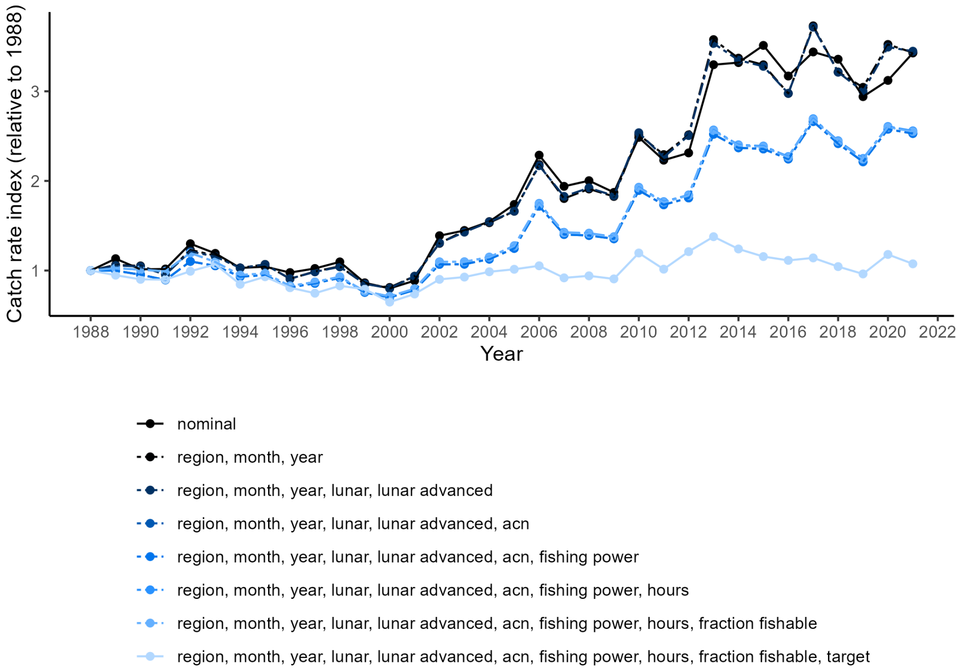


Figure A.1: Influence of model terms on sand bug standardised catch rates using only logbook records where catches were greater than zero. For visual comparison of model trends, annual catch rates indices are shown which have been standardised to equal 1 in 1988 when logbook records began.

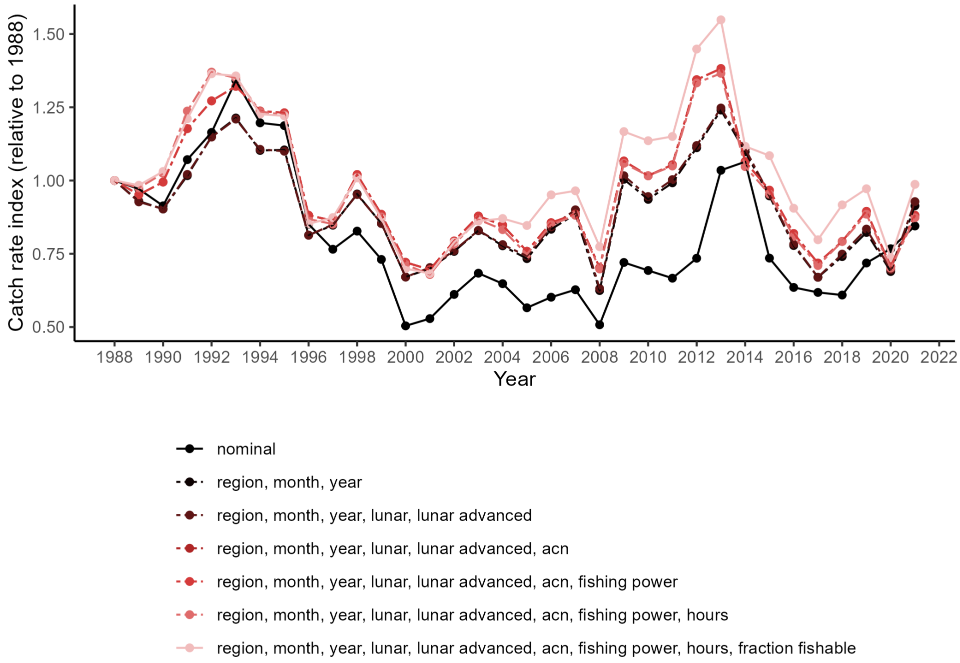


Figure A.2: Influence of model terms on mud bug standardised catch rates using only logbook records where catches were greater than zero. For visual comparison of model trends, annual catch rates indices are shown which have been standardised to equal 1 in 1988 when logbook records began.

A.1.2 Residuals

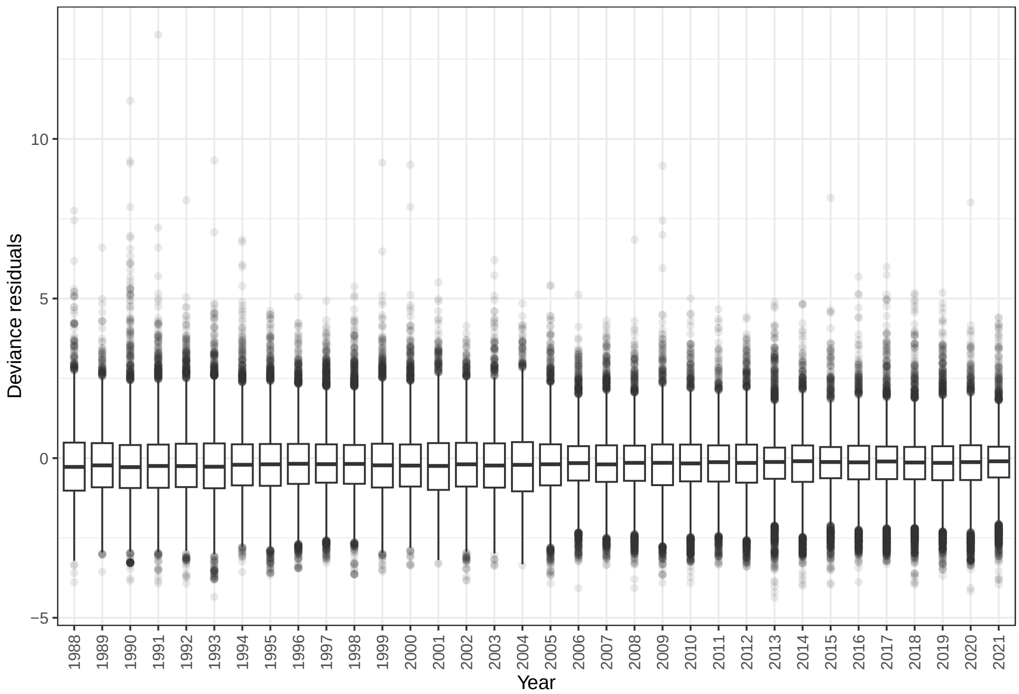


Figure A.3: Standardised residuals by year for sand bug standardised catch rate model

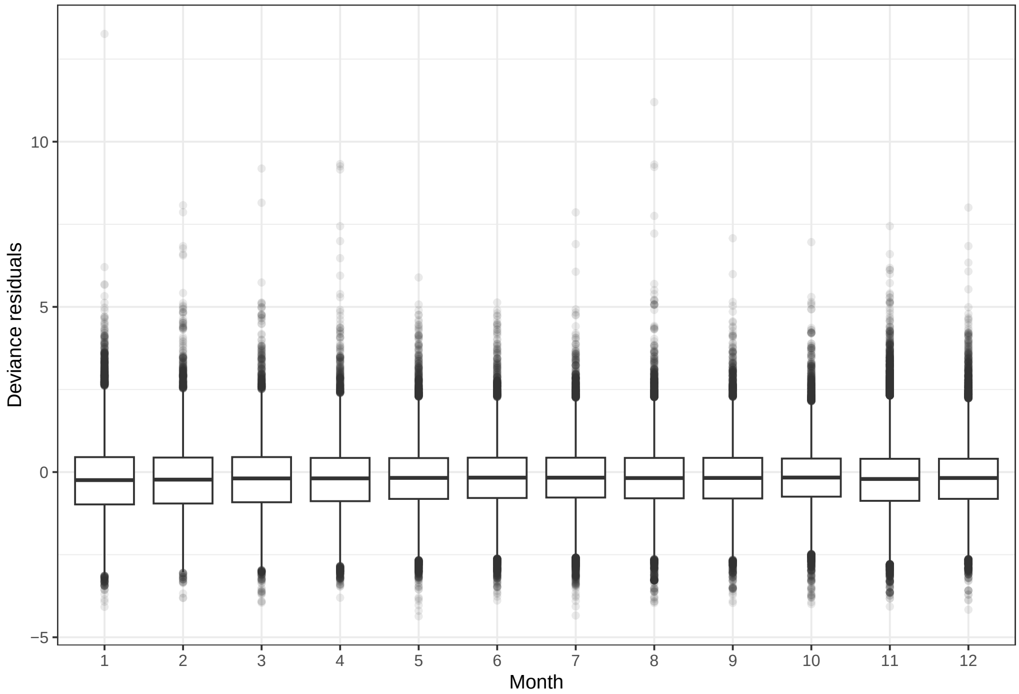


Figure A.4: Standardised residuals by month for sand bug standardised catch rate model

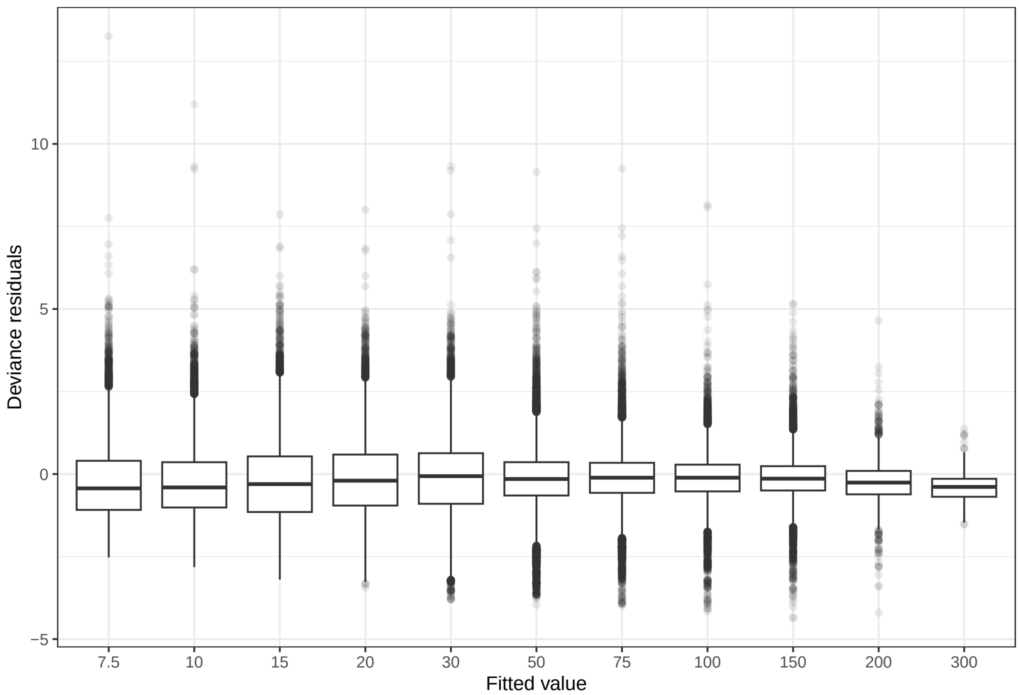


Figure A.5: Standardised residual for sand bug standardised catch rate model

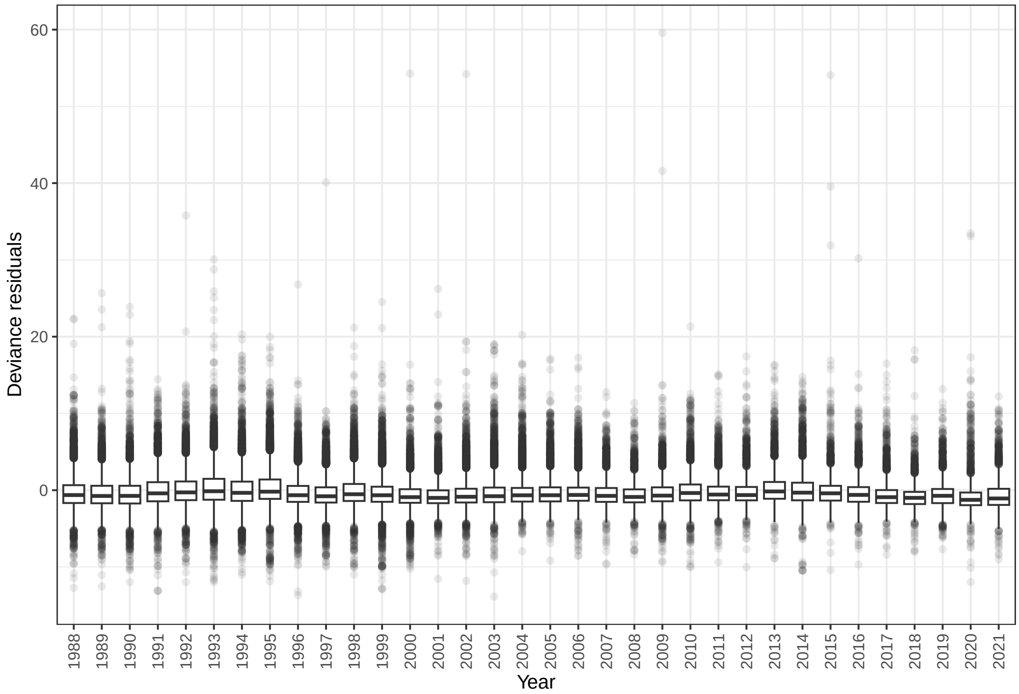


Figure A.6: Standardised residuals by year for mud bug standardised catch rate model

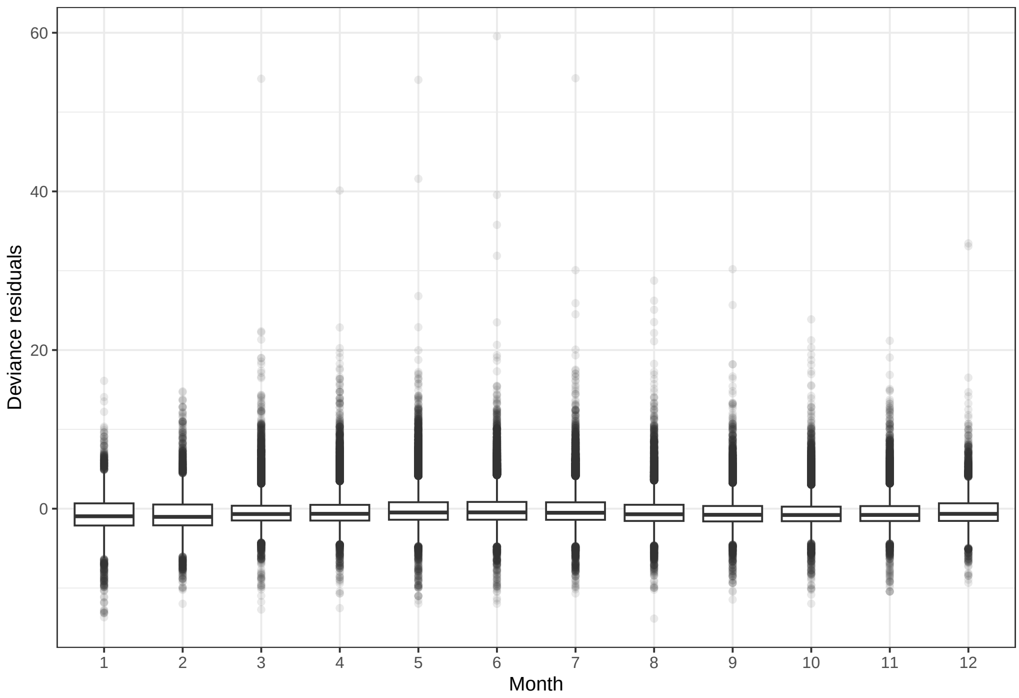


Figure A.7: Standardised residuals by month for mud bug standardised catch rate model

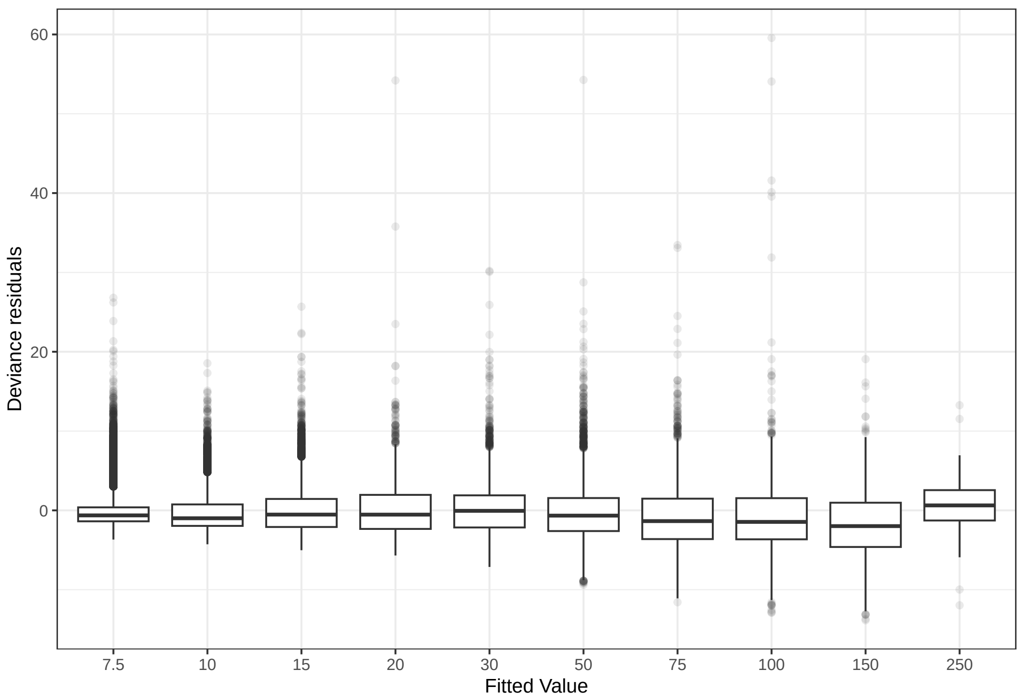


Figure A.8: Standardised residuals for mud bug standardised catch rate model

A.1.3 Fleet profile

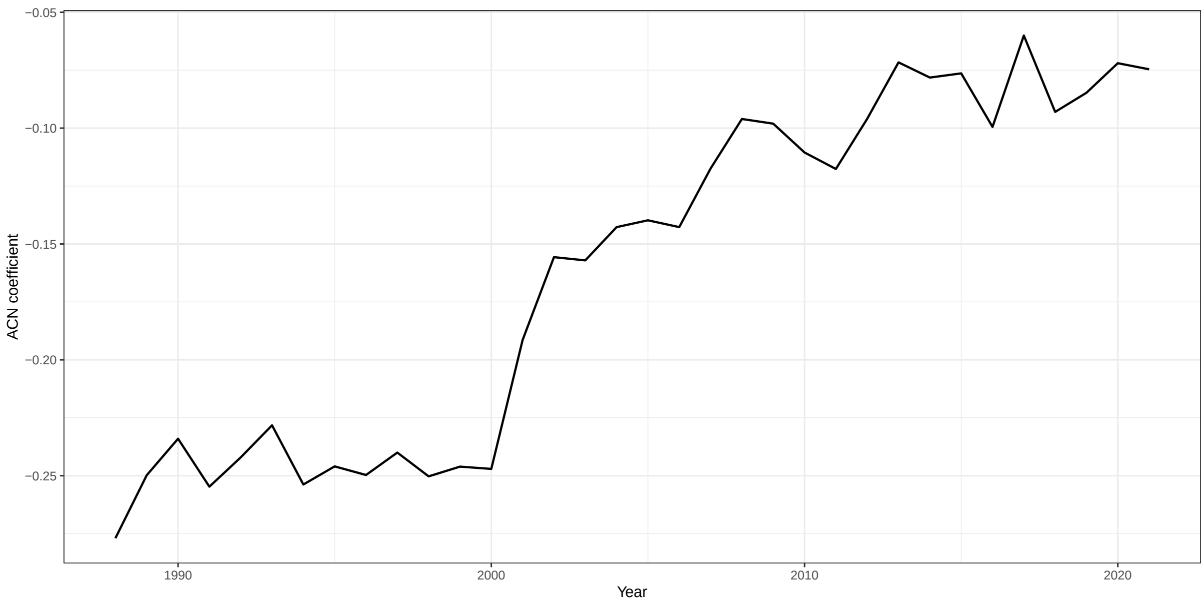


Figure A.9: Yearly ACN effect through time for sand bug fleet

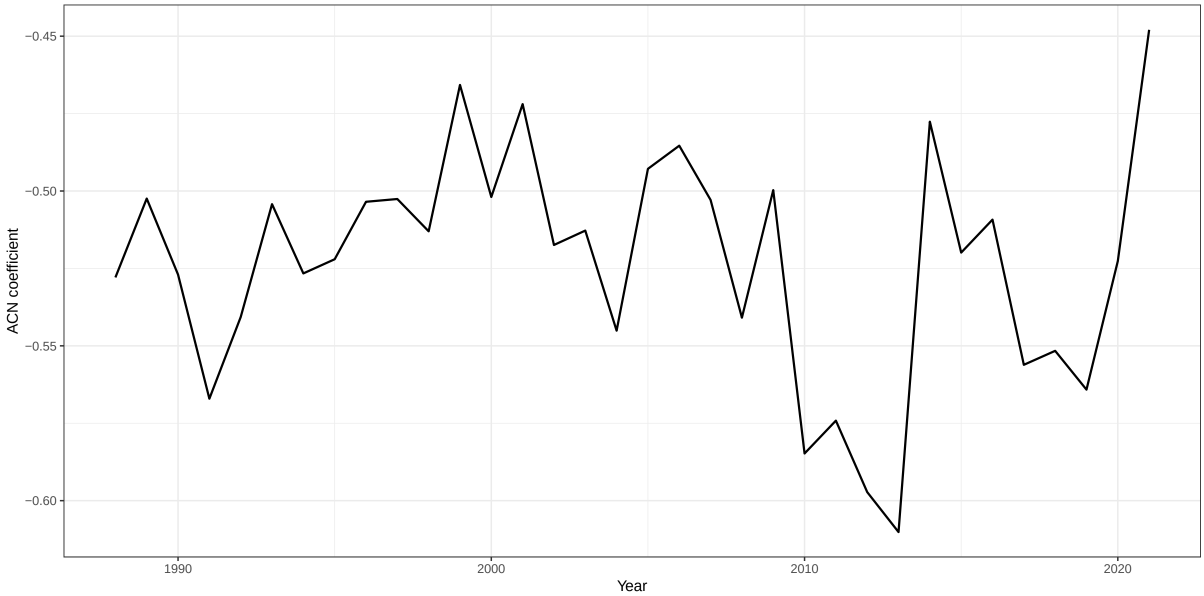


Figure A.10: Yearly ACN effect through time for mud bug fleet

A.1.4 Fishing power (gear)

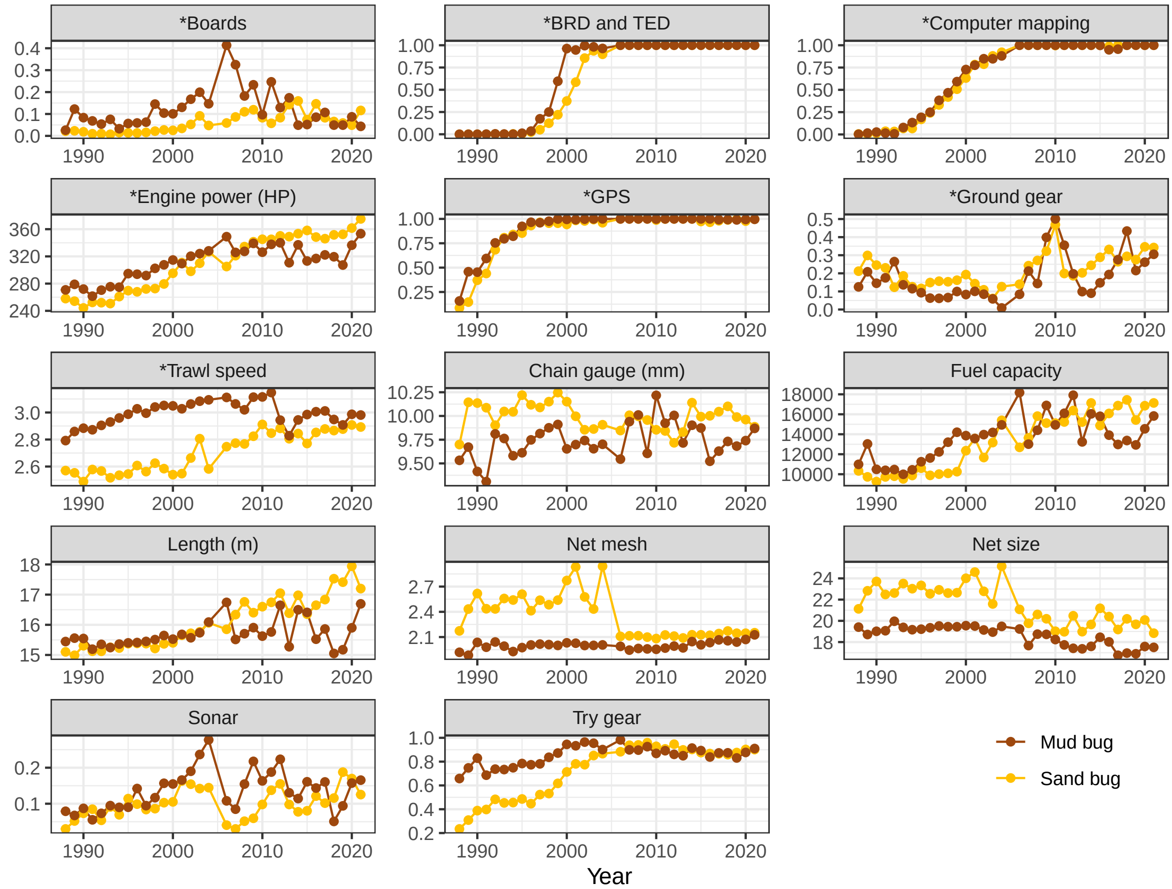


Figure A.11: Fishing power gear trends—asterisks represent variables that were included in the fishing power model

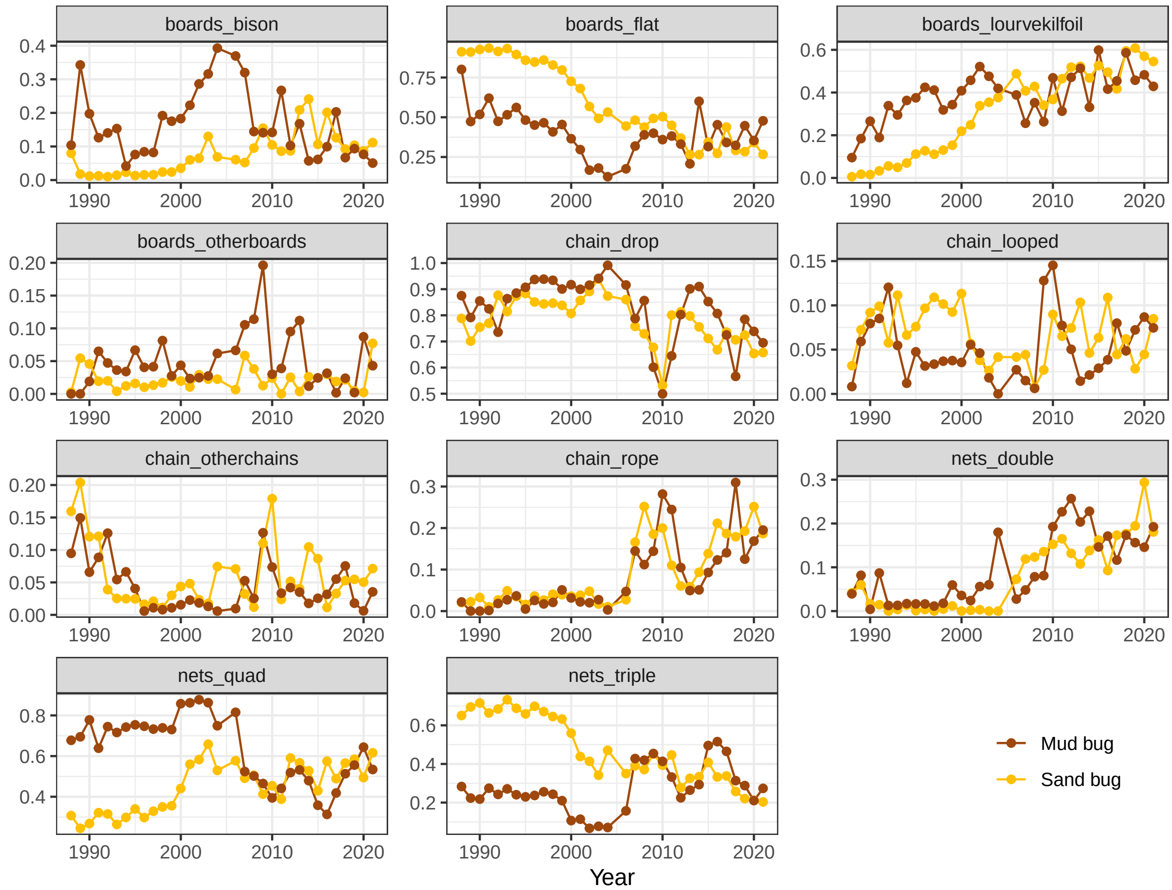


Figure A.12: Fishing power gear trends continued

A.2 Biological data

A.2.1 Length-at-age

Growth curves from (Courtney 1997) as shown in red were used in all scenarios except scenario 12 for both sand (Figure A.13) and mud bugs (Figure A.14). Snceario 12 for both sand (Figure A.13) and mud (Figure A.14) bugs used growth curves from (Jones 1988) as shown in black.

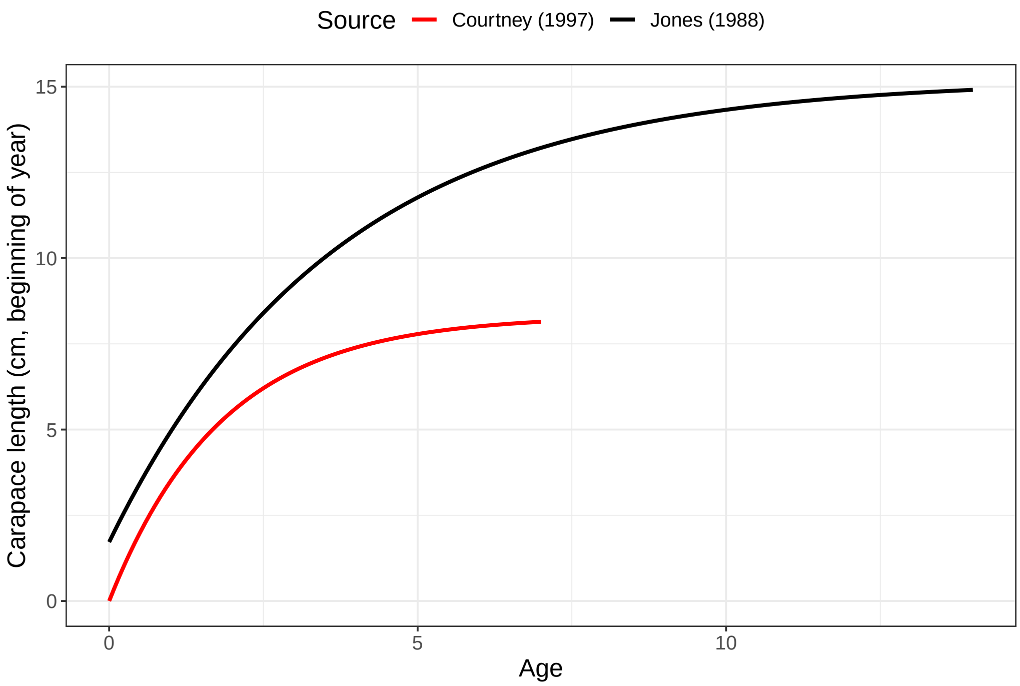


Figure A.13: Growth curves from Jones (1988) and Courtney (1997) applied to the sand bug model

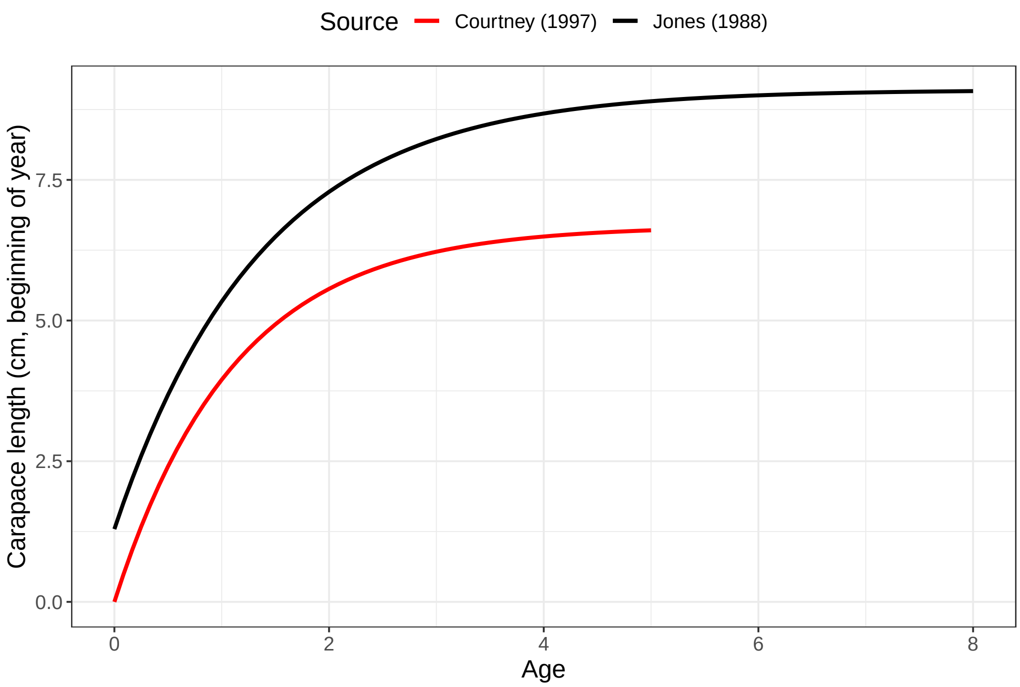


Figure A.14: Growth curves from Jones (1988) and Courtney (1992) applied to the mud bug model

A.2.2 Seasonal spawning

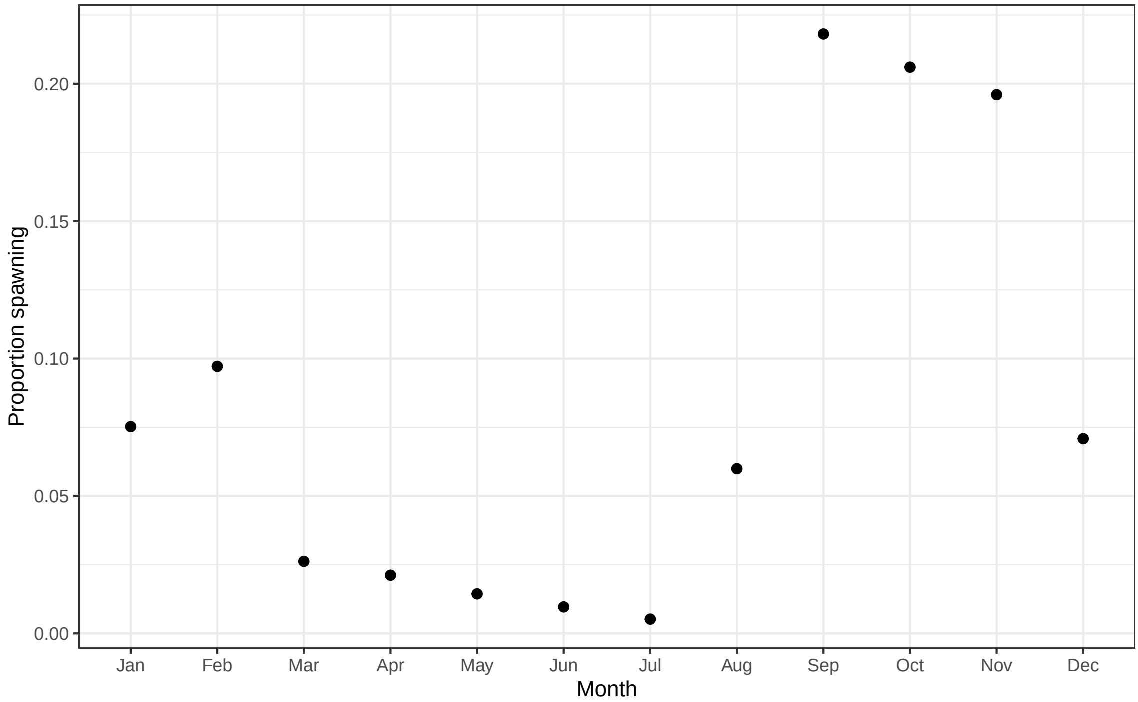


Figure A.15: Proportion of sand and mud bugs spawning each month

A.2.3 Recruitment

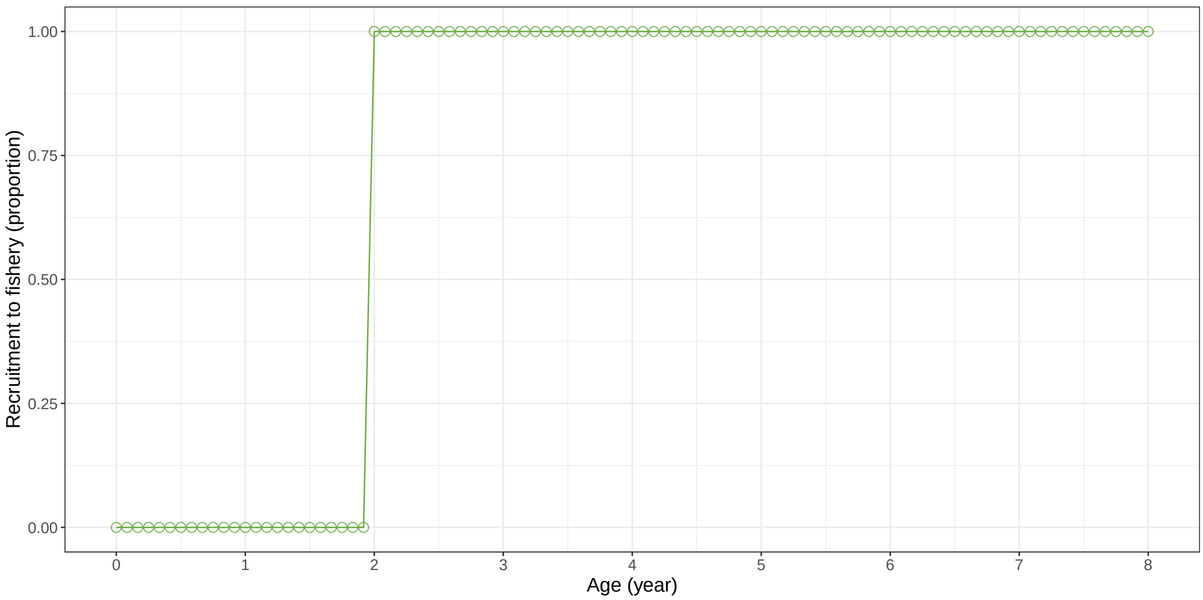


Figure A.16: Knife-edged recruitment for sand bugs and mud bugs

Appendix B Model outputs

B.1 MCMC Diagnostics

B.1.1 Posterior density

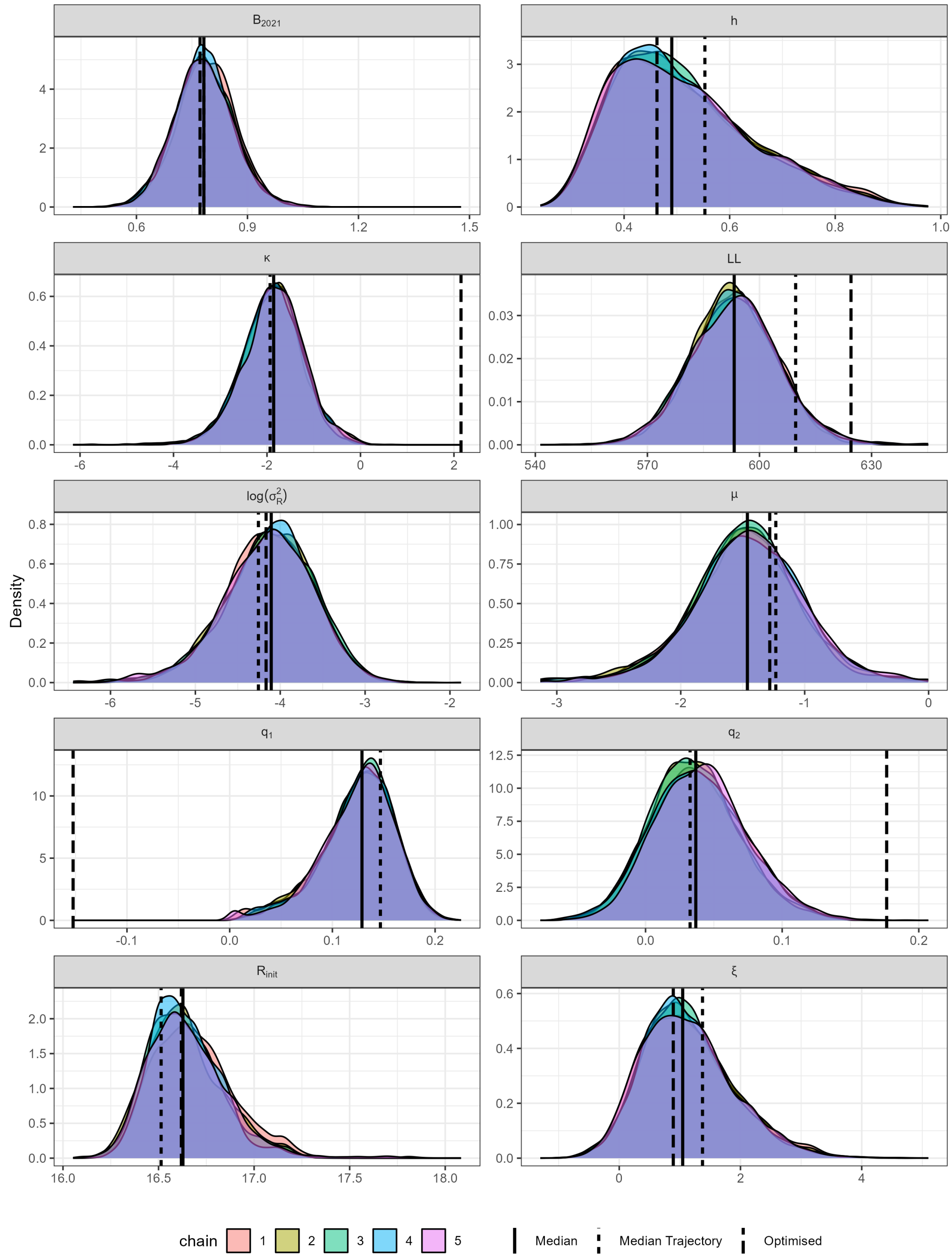


Figure B.1: Posterior density of MCMC chains for sand bugs scenario 1. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

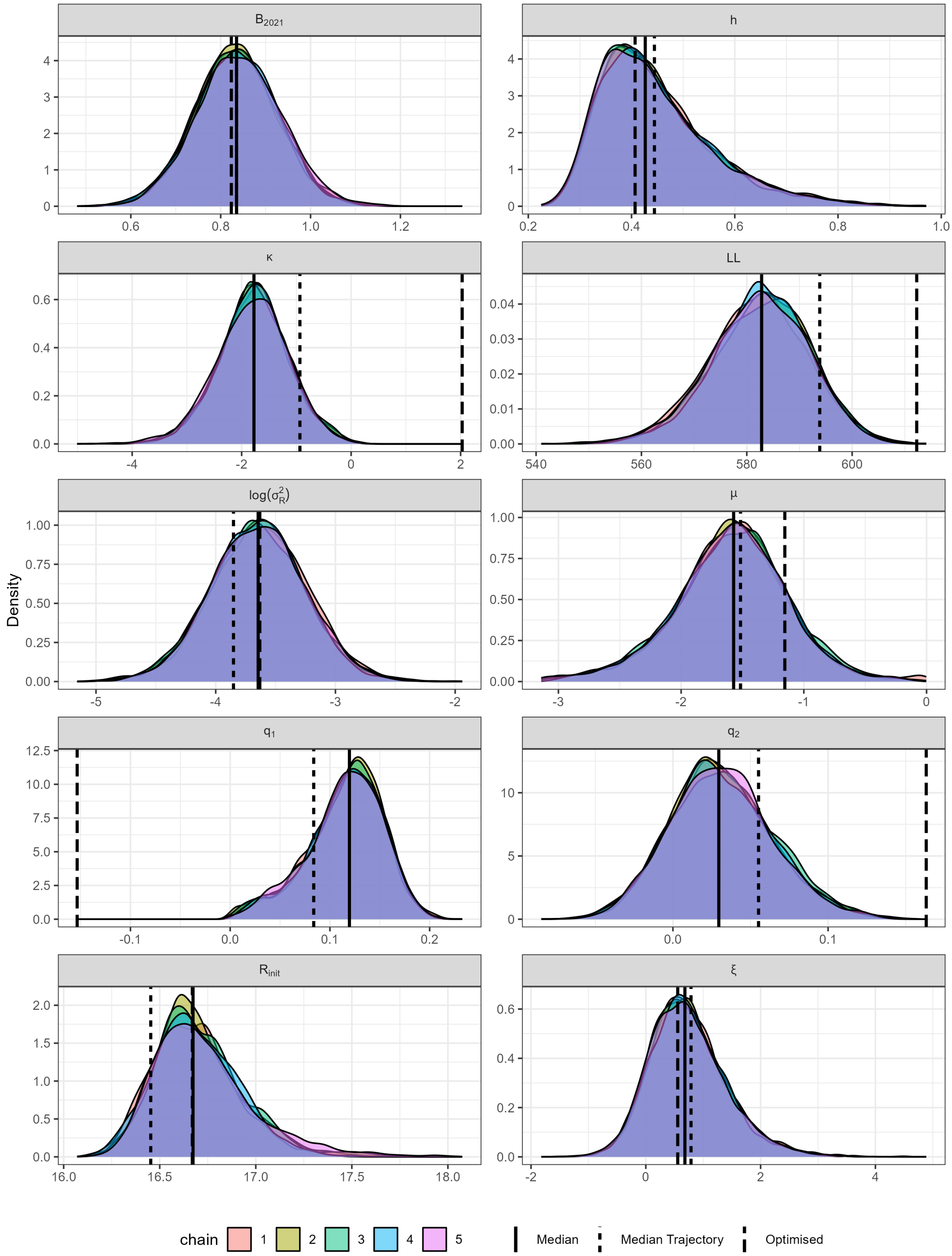


Figure B.2: Posterior density of MCMC chains for sand bugs scenario 2. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

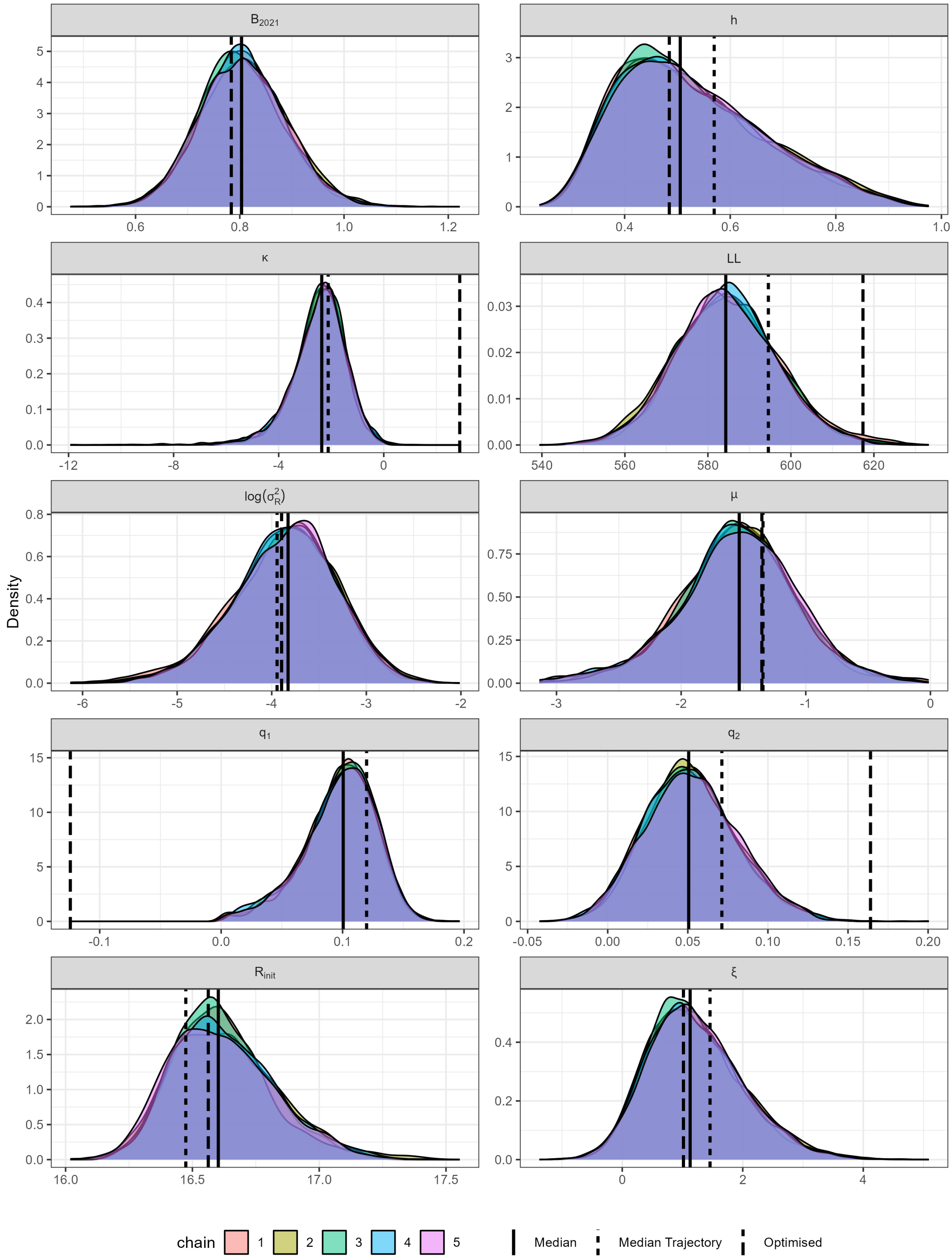


Figure B.3: Posterior density of MCMC chains for sand bugs scenario 3. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

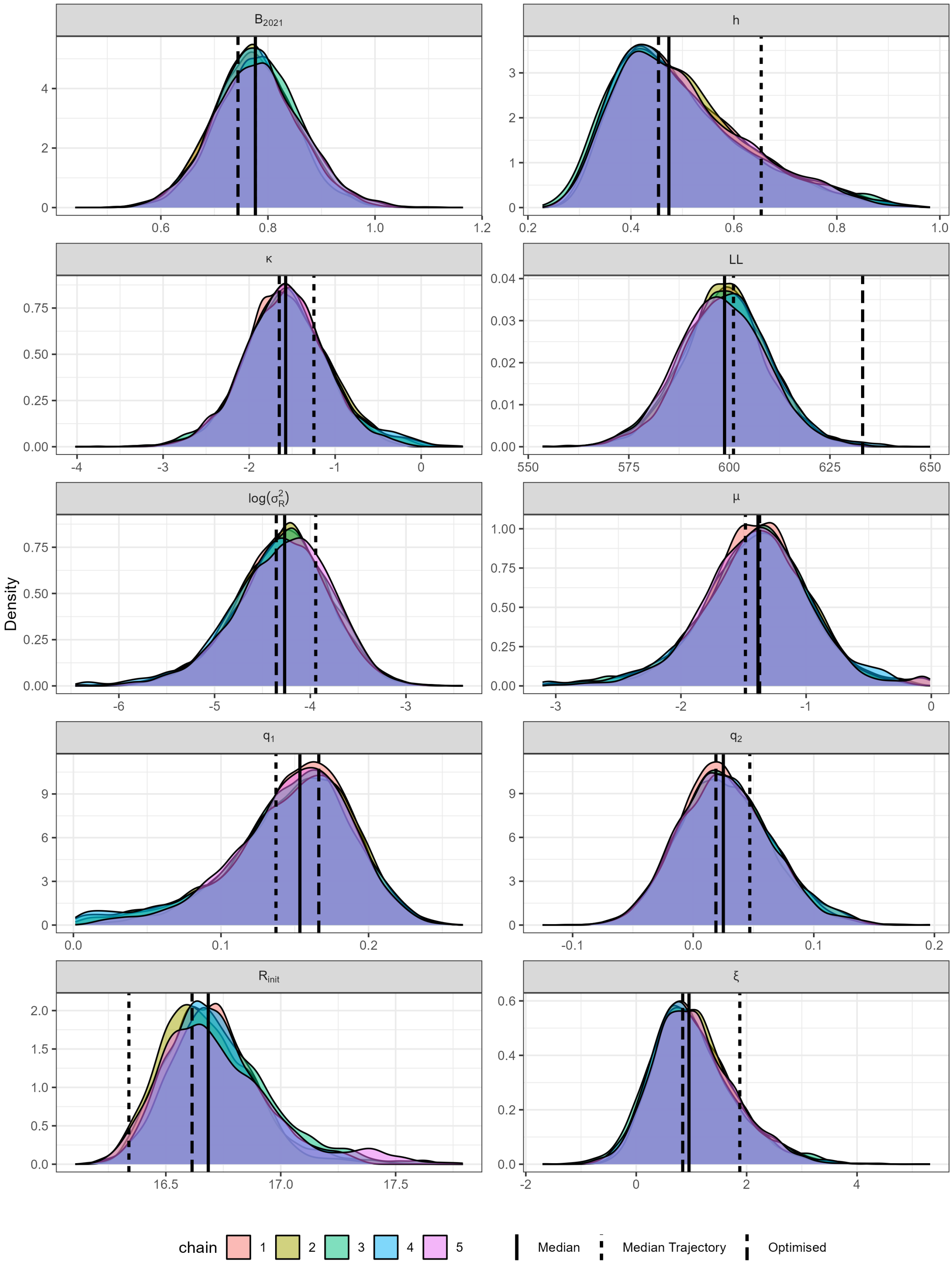


Figure B.4: Posterior density of MCMC chains for sand bugs scenario 4. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

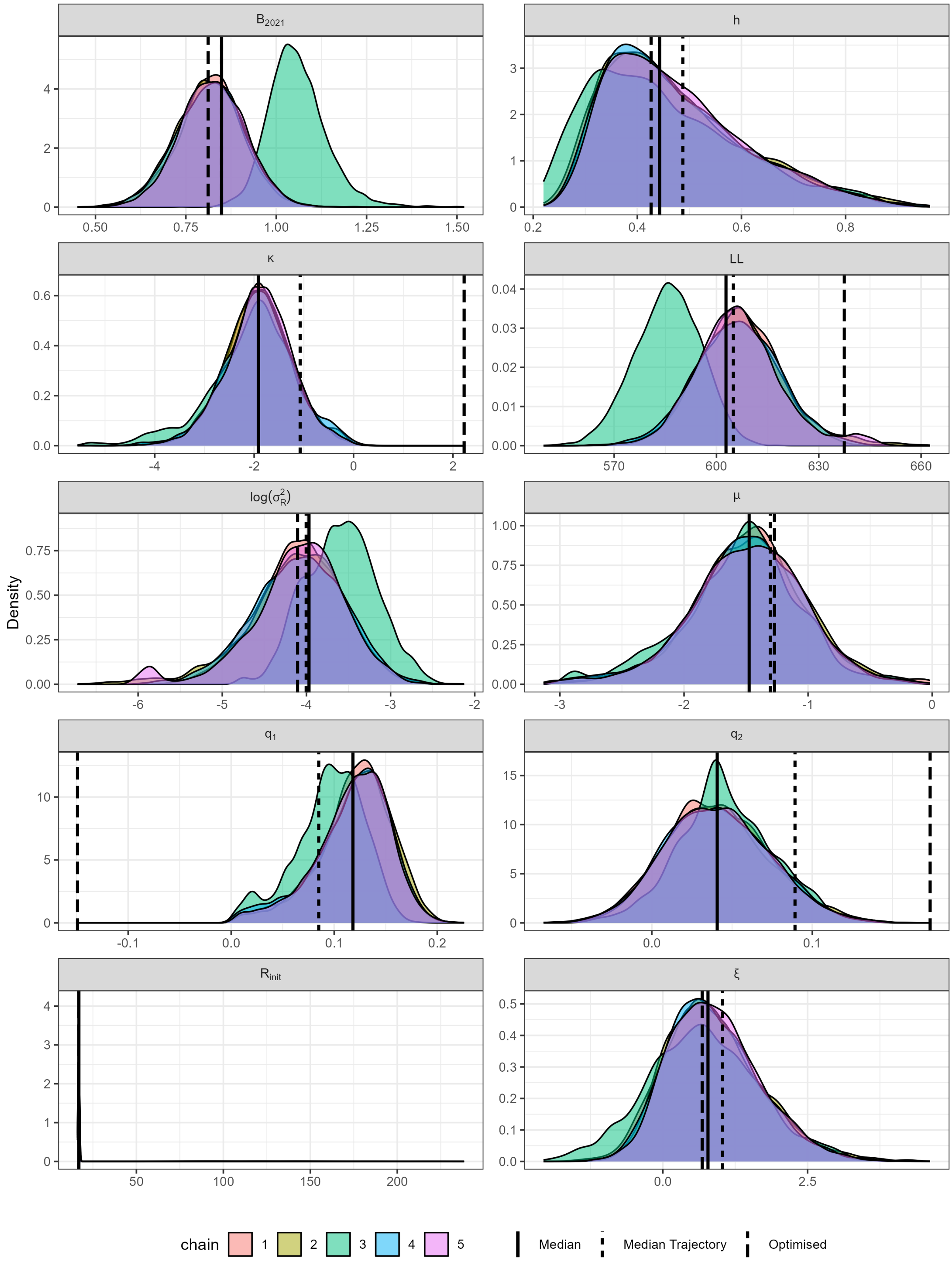


Figure B.5: Posterior density of MCMC chains for sand bugs scenario 5. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

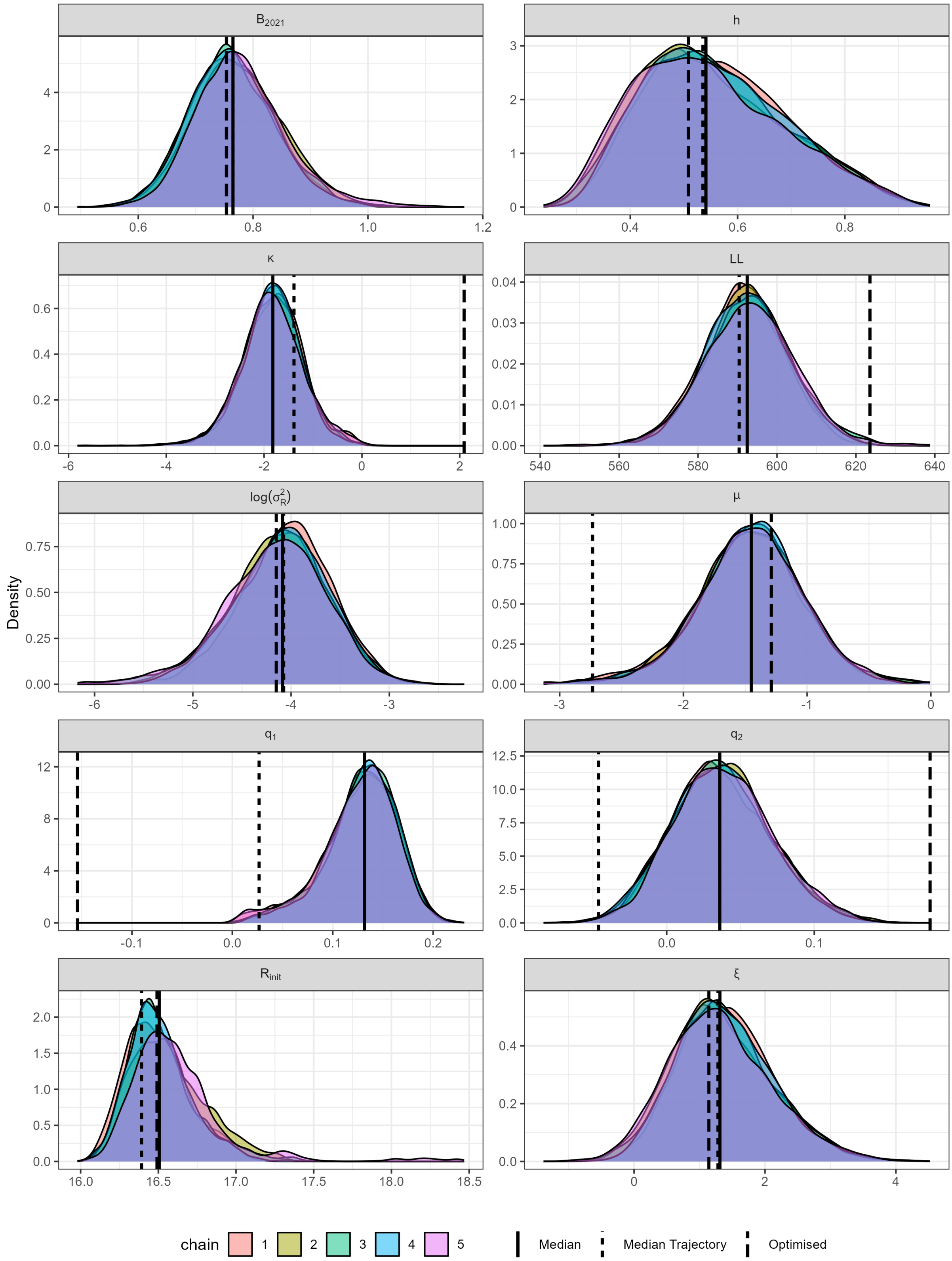


Figure B.6: Posterior density of MCMC chains for sand bugs scenario 6. ‘Median’ line shows median parameter value for MCMC chains. ‘Median Trajectory’ line shows parameter value for trajectory resulting in median biomass in 2021. ‘Optimised’ shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

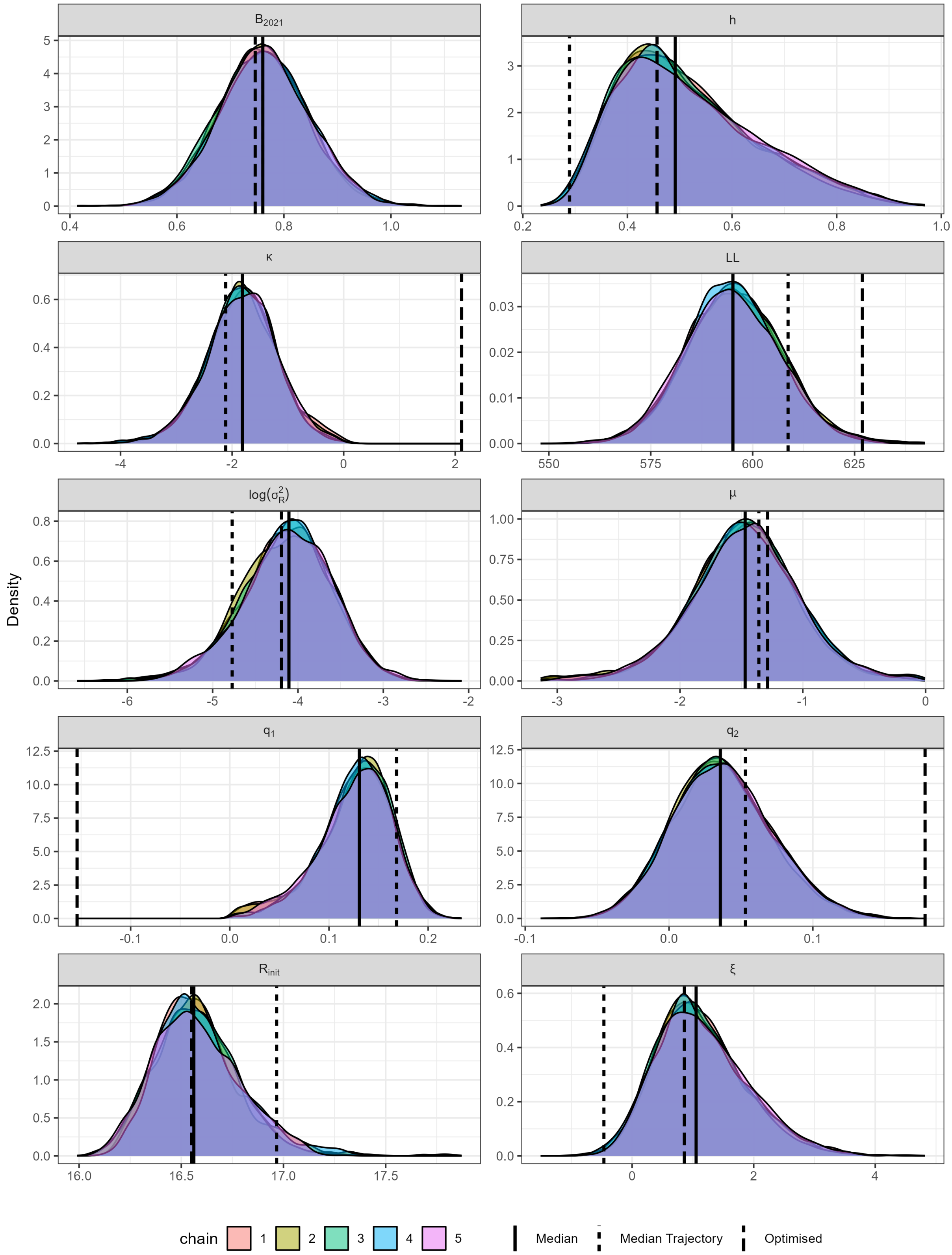


Figure B.7: Posterior density of MCMC chains for sand bugs scenario 7. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

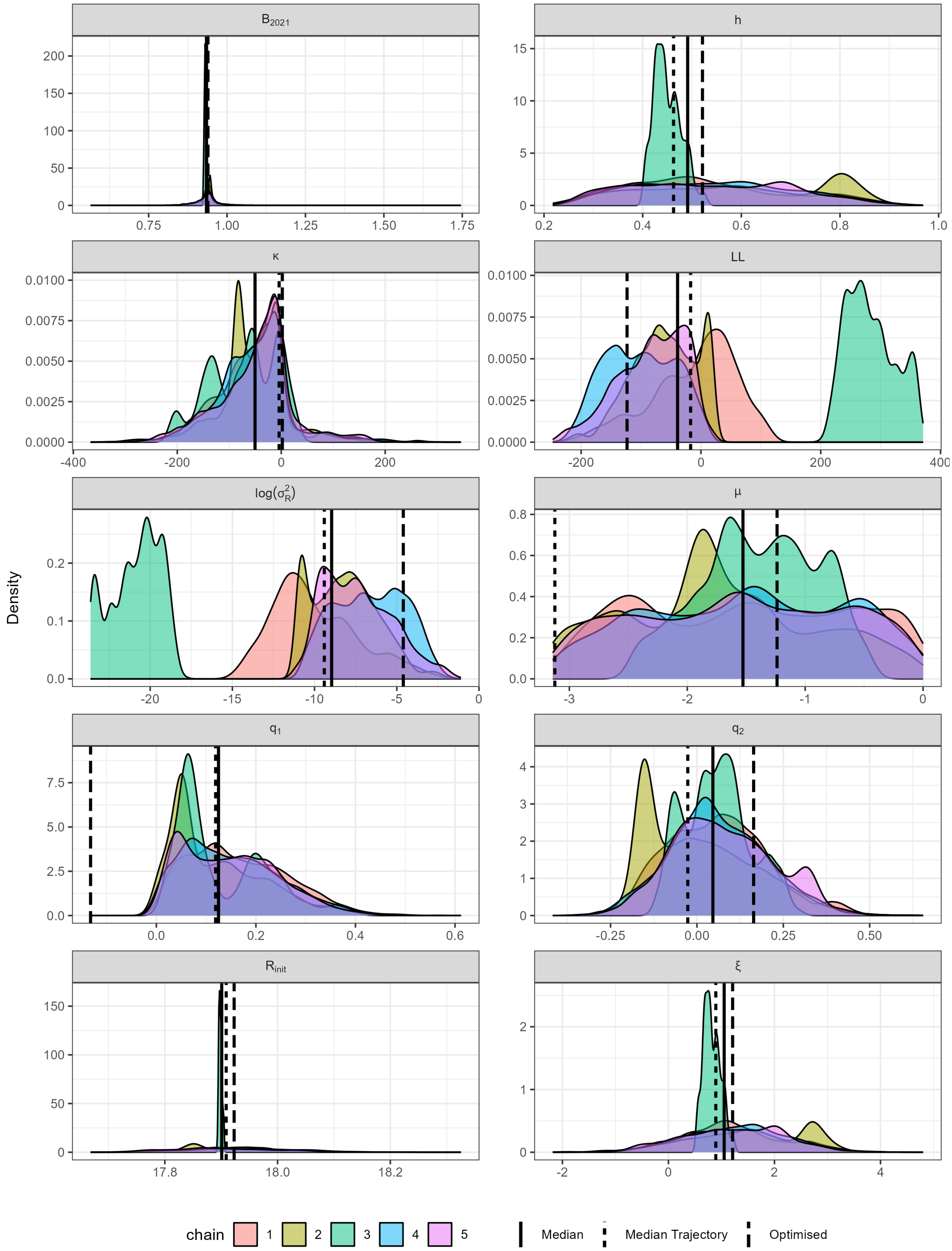


Figure B.8: Posterior density of MCMC chains for sand bugs scenario 8. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

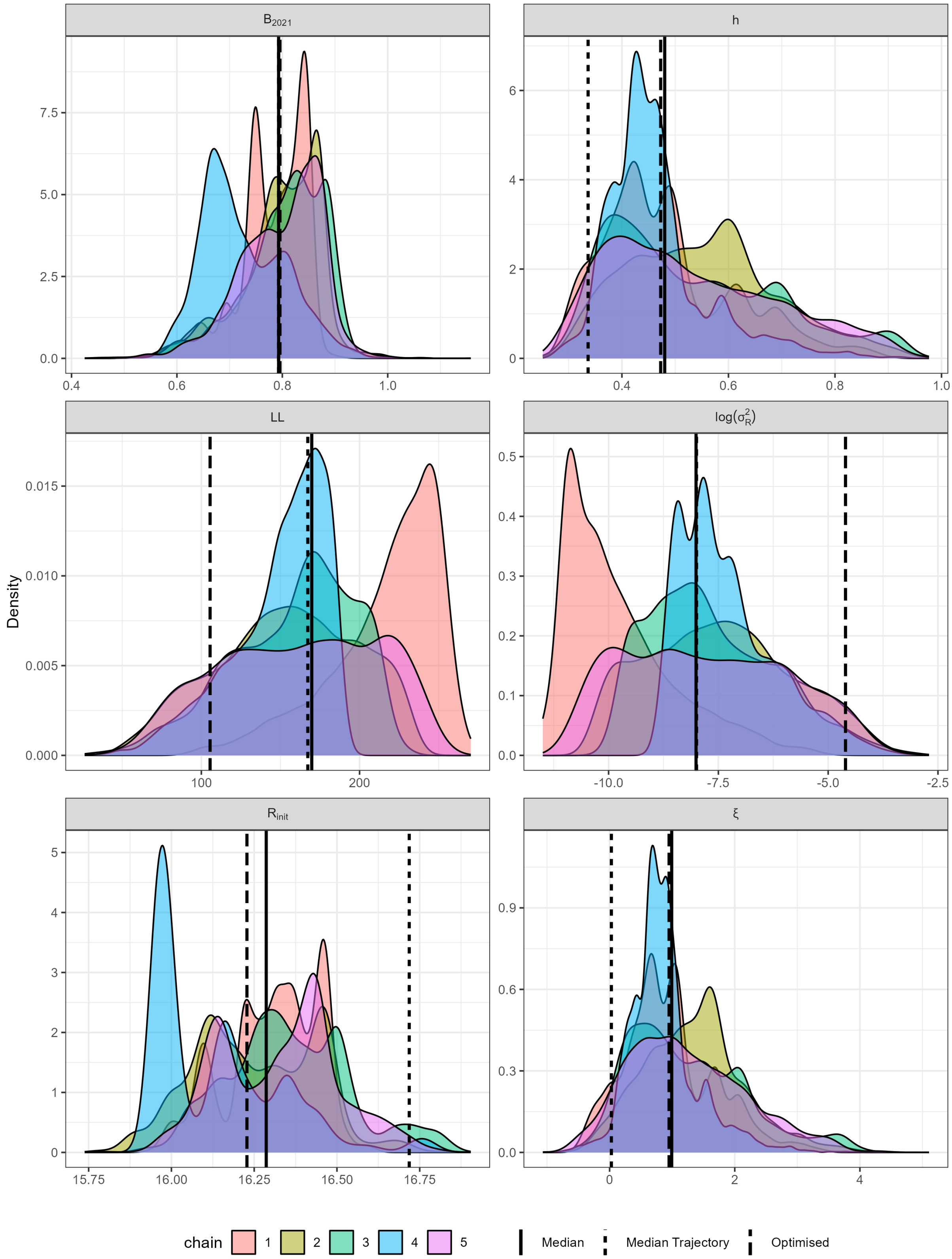


Figure B.9: Posterior density of MCMC chains for sand bugs scenario 9. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

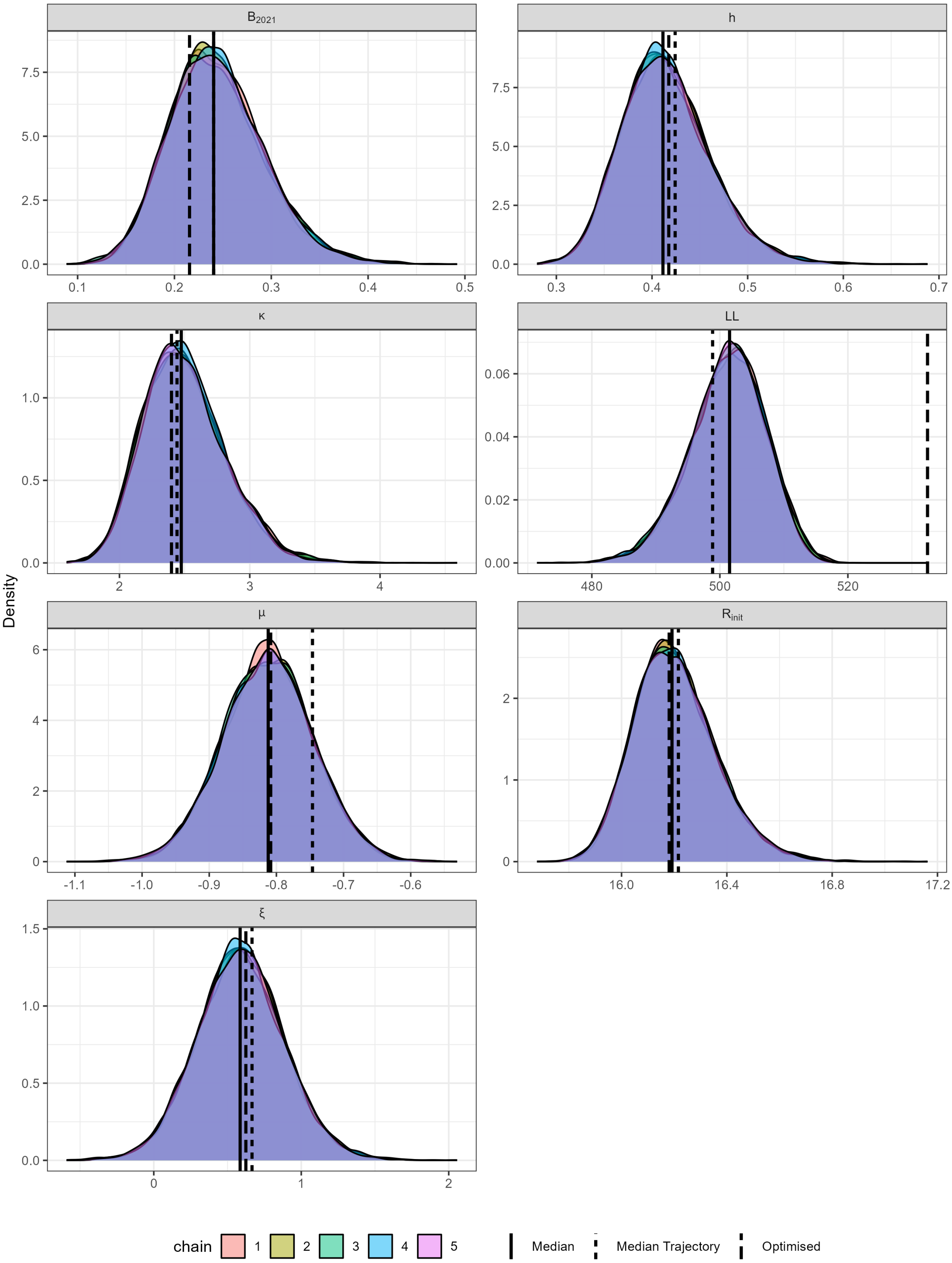


Figure B.10: Posterior density of MCMC chains for sand bugs scenario 10. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

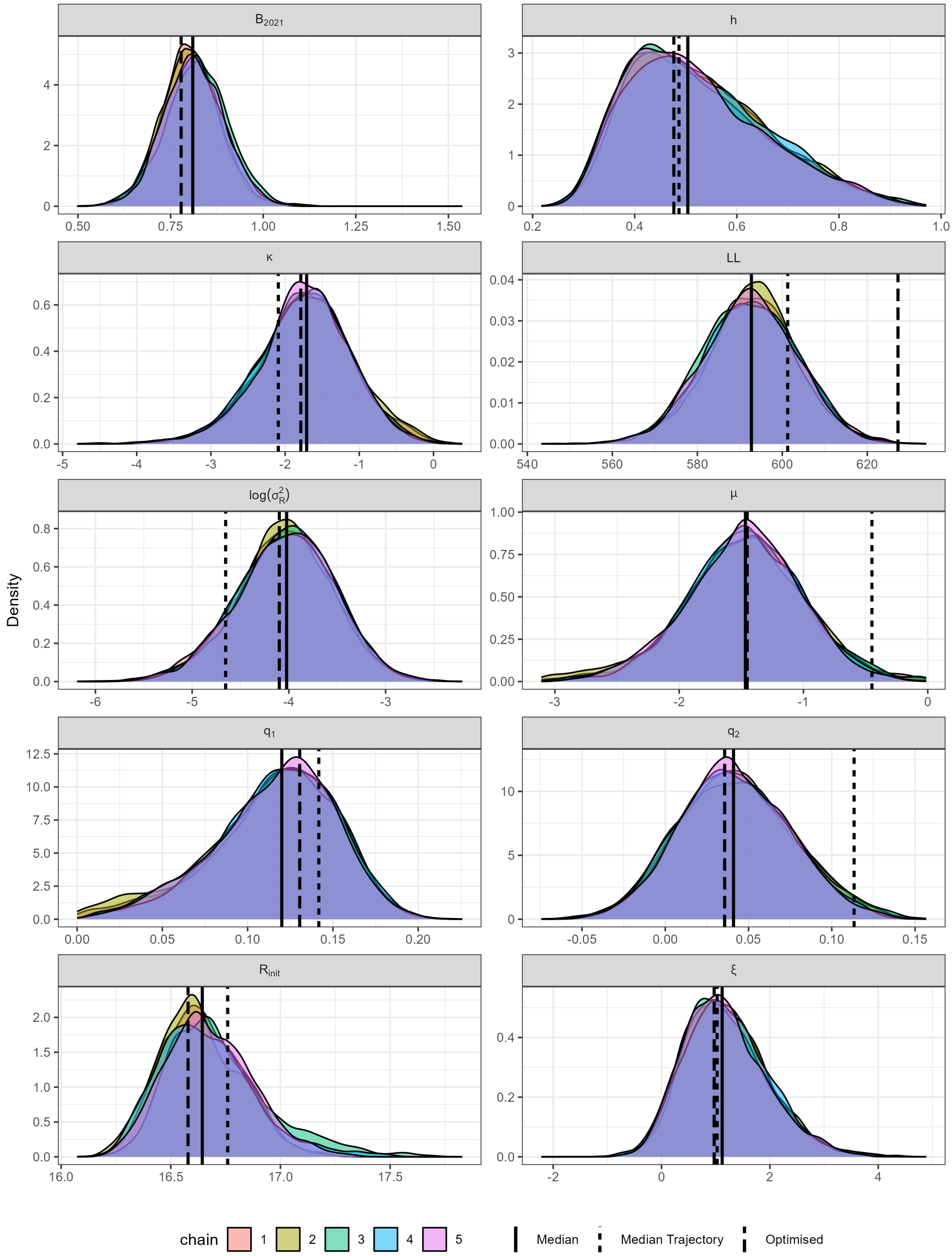


Figure B.11: Posterior density of MCMC chains for sand bugs scenario 11. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

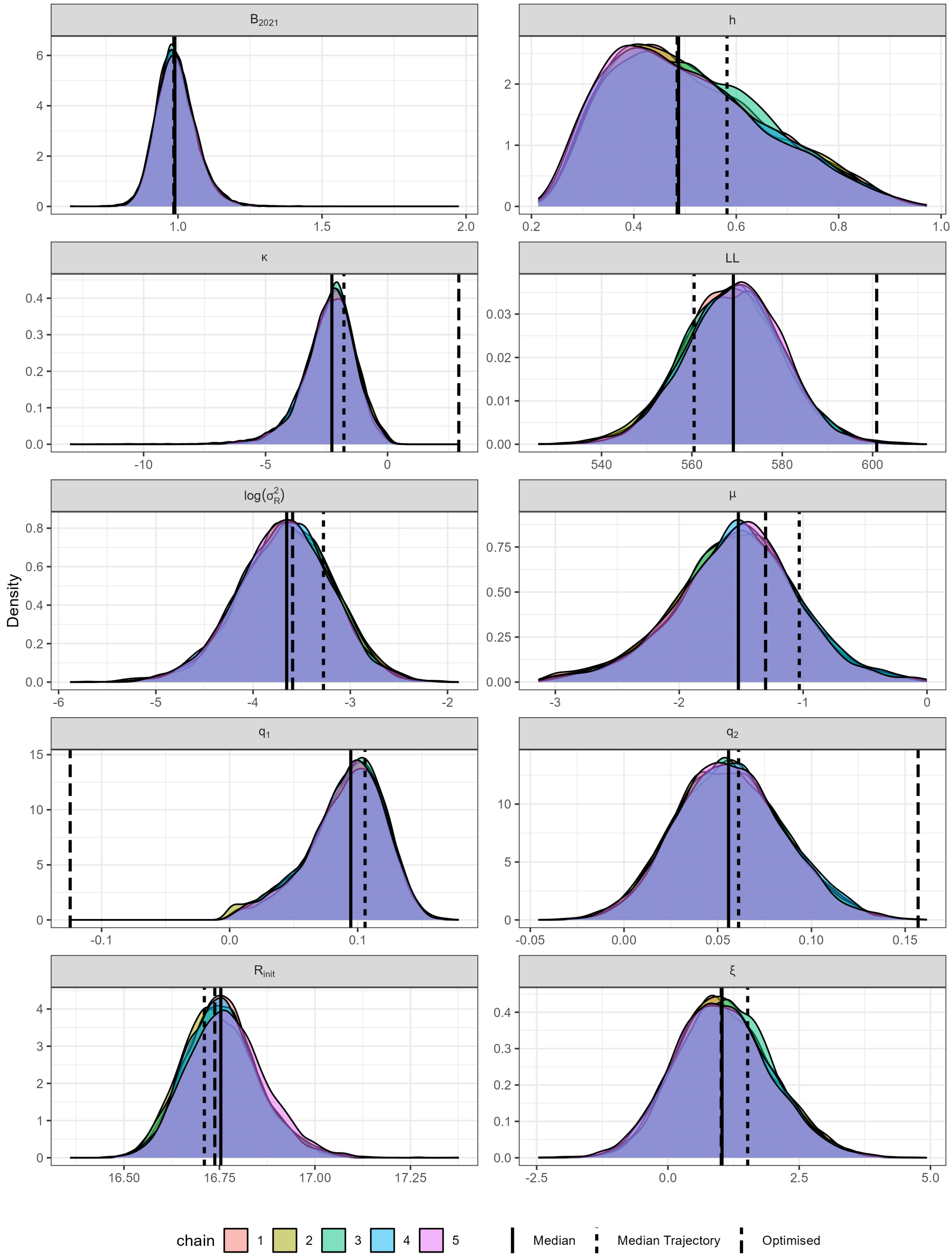


Figure B.12: Posterior density of MCMC chains for sand bugs scenario 12. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

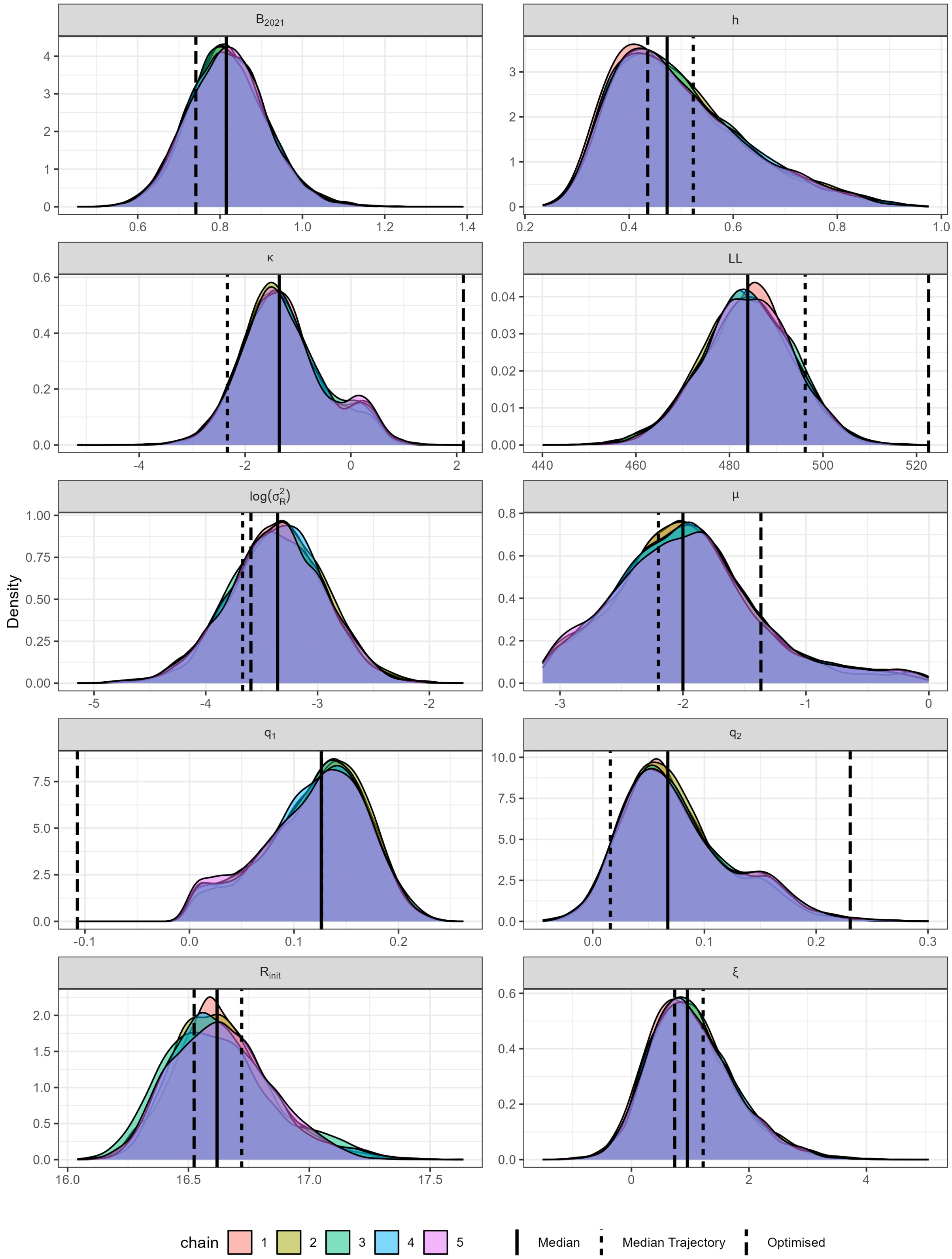


Figure B.13: Posterior density of MCMC chains for sand bugs scenario 13. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

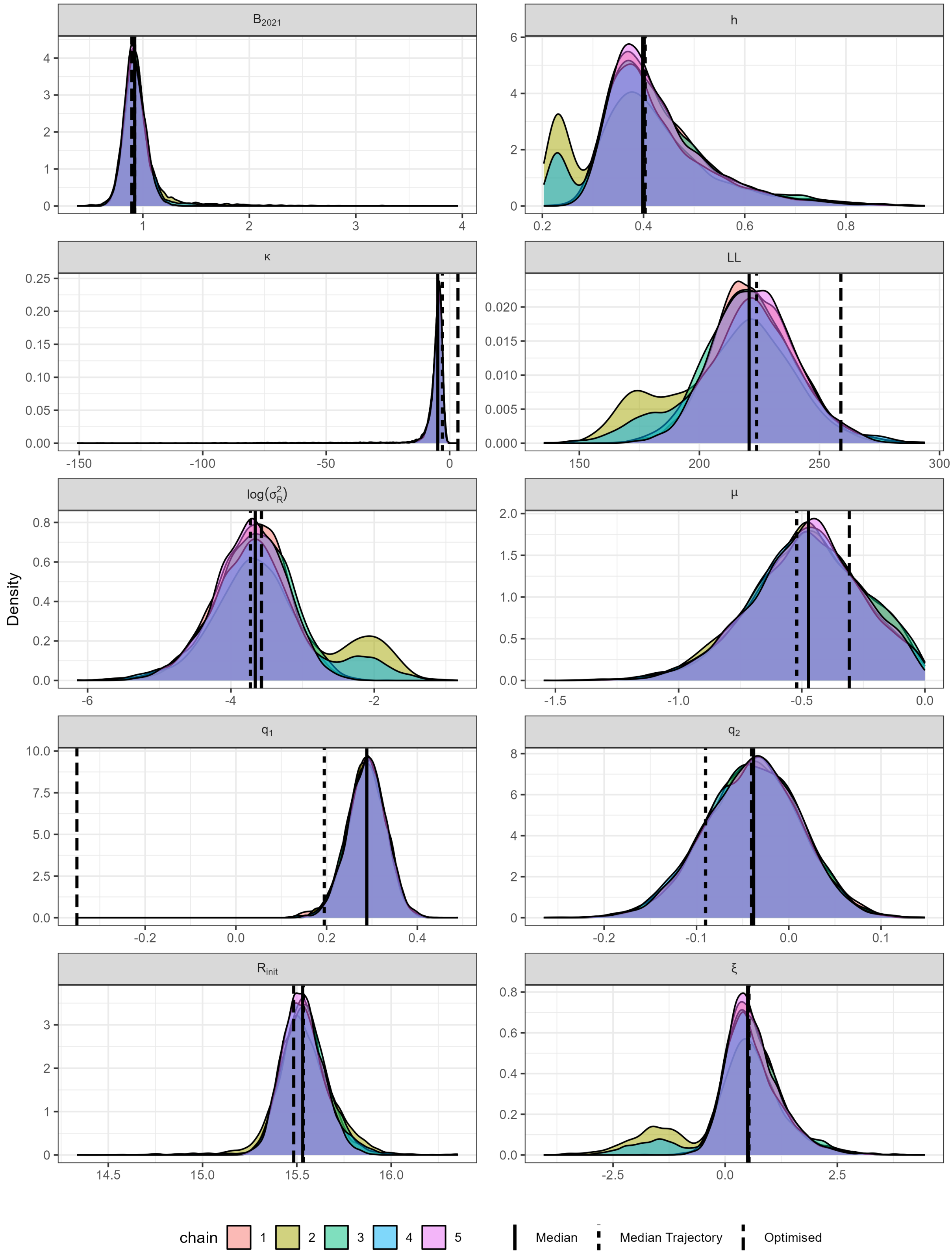


Figure B.14: Posterior density of MCMC chains for mud bugs scenario 1. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

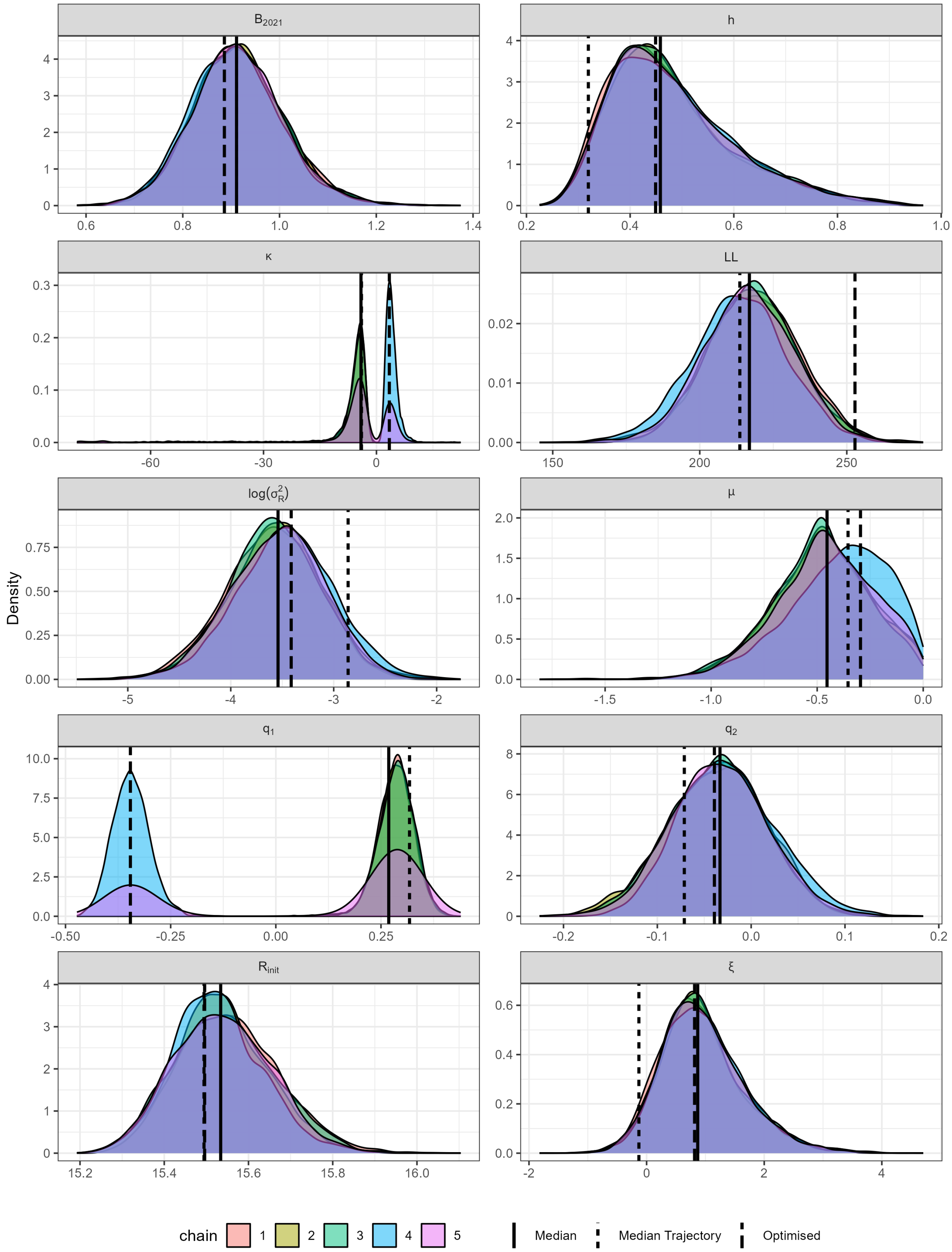


Figure B.15: Posterior density of MCMC chains for mud bugs scenario 2. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

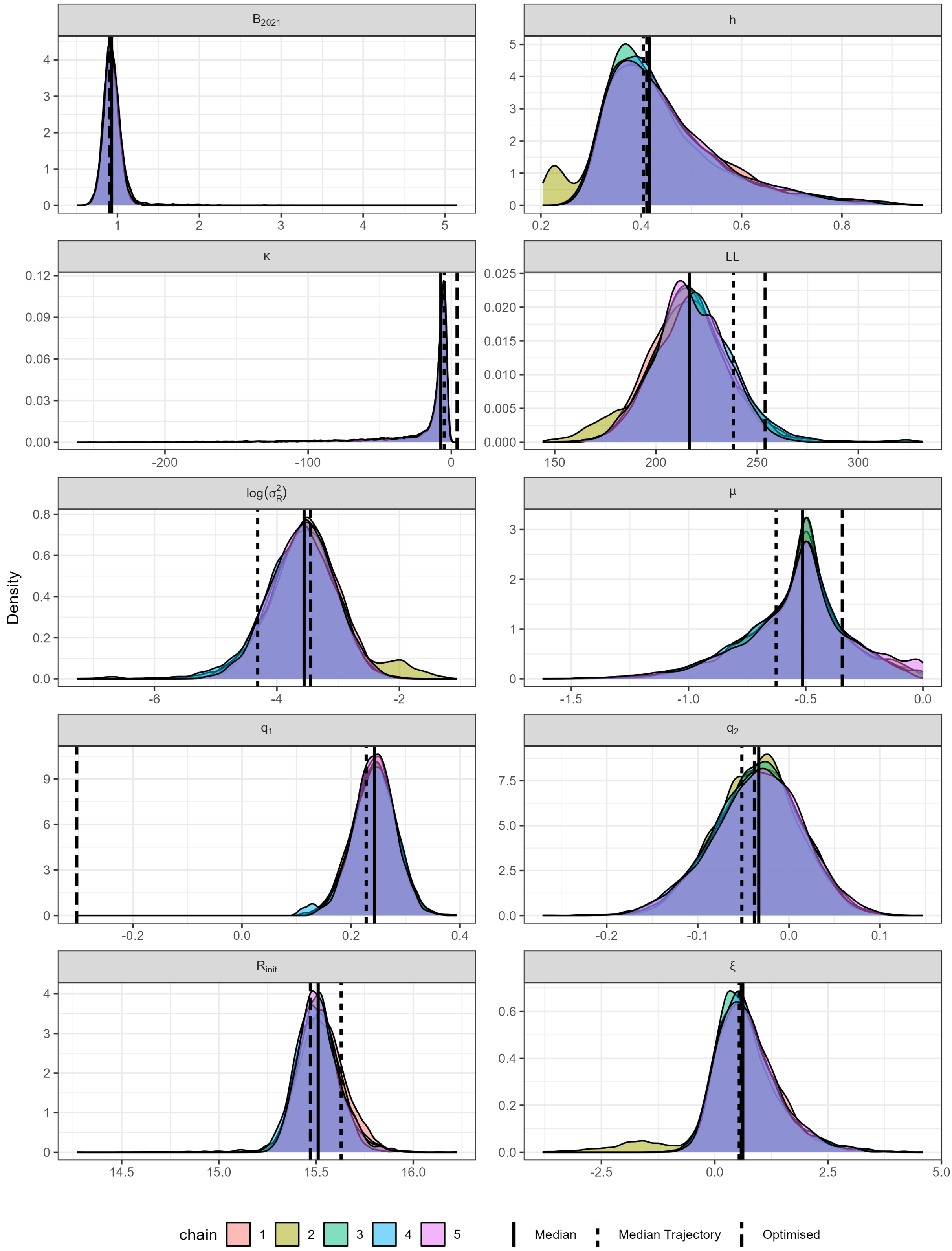


Figure B.16: Posterior density of MCMC chains for mud bugs scenario 3. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

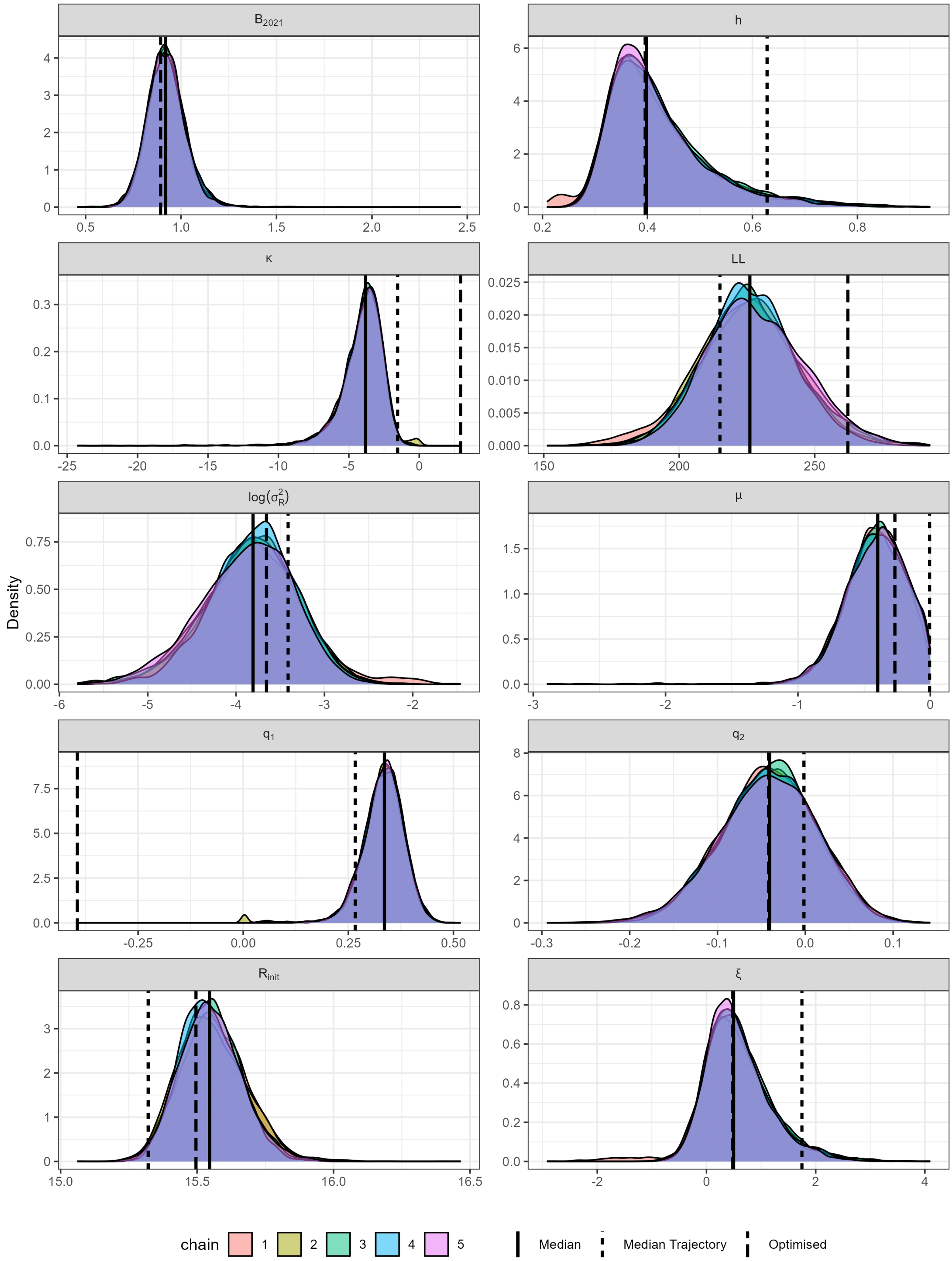


Figure B.17: Posterior density of MCMC chains for mud bugs scenario 4. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

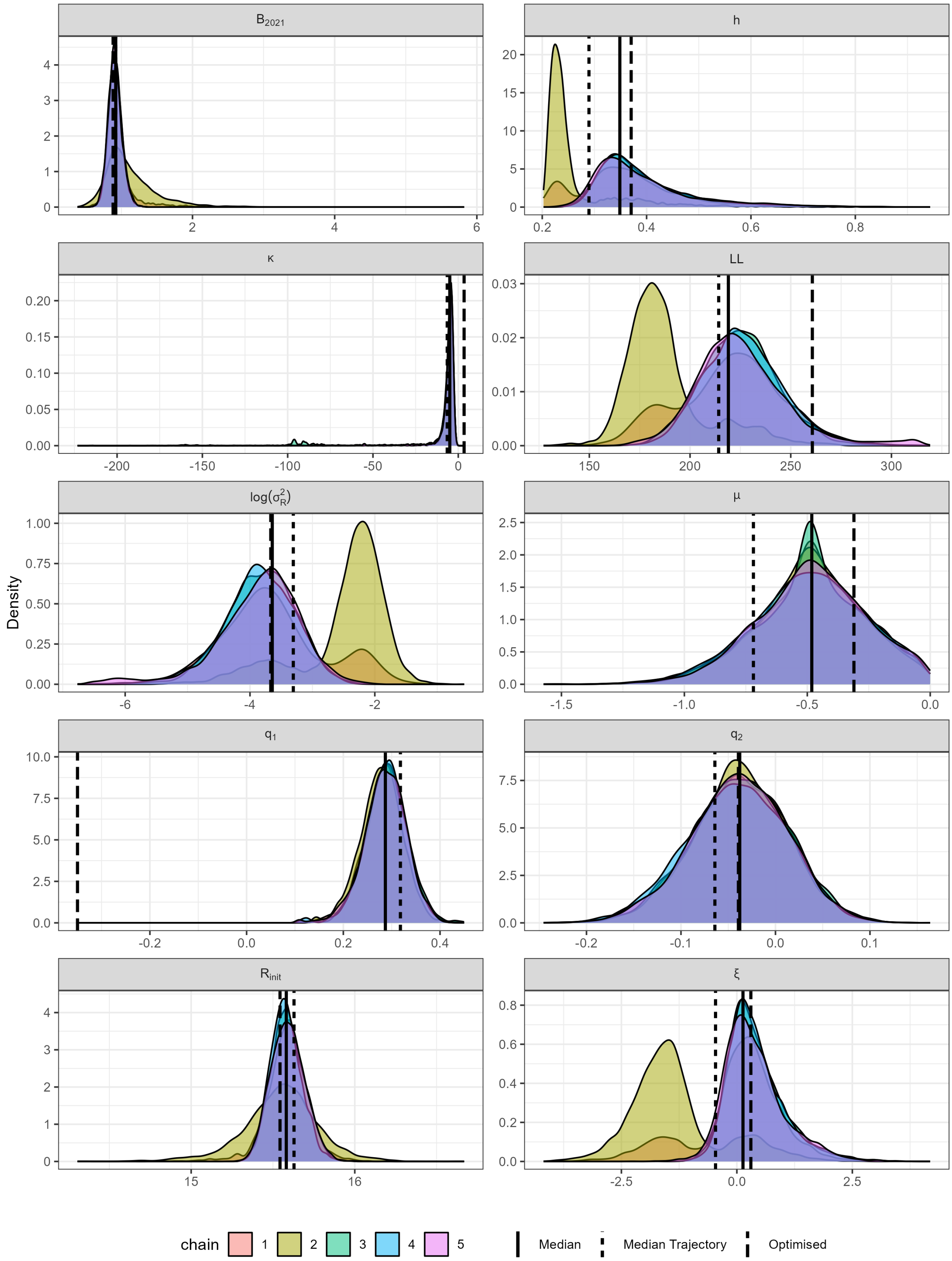


Figure B.18: Posterior density of MCMC chains for mud bugs scenario 5. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

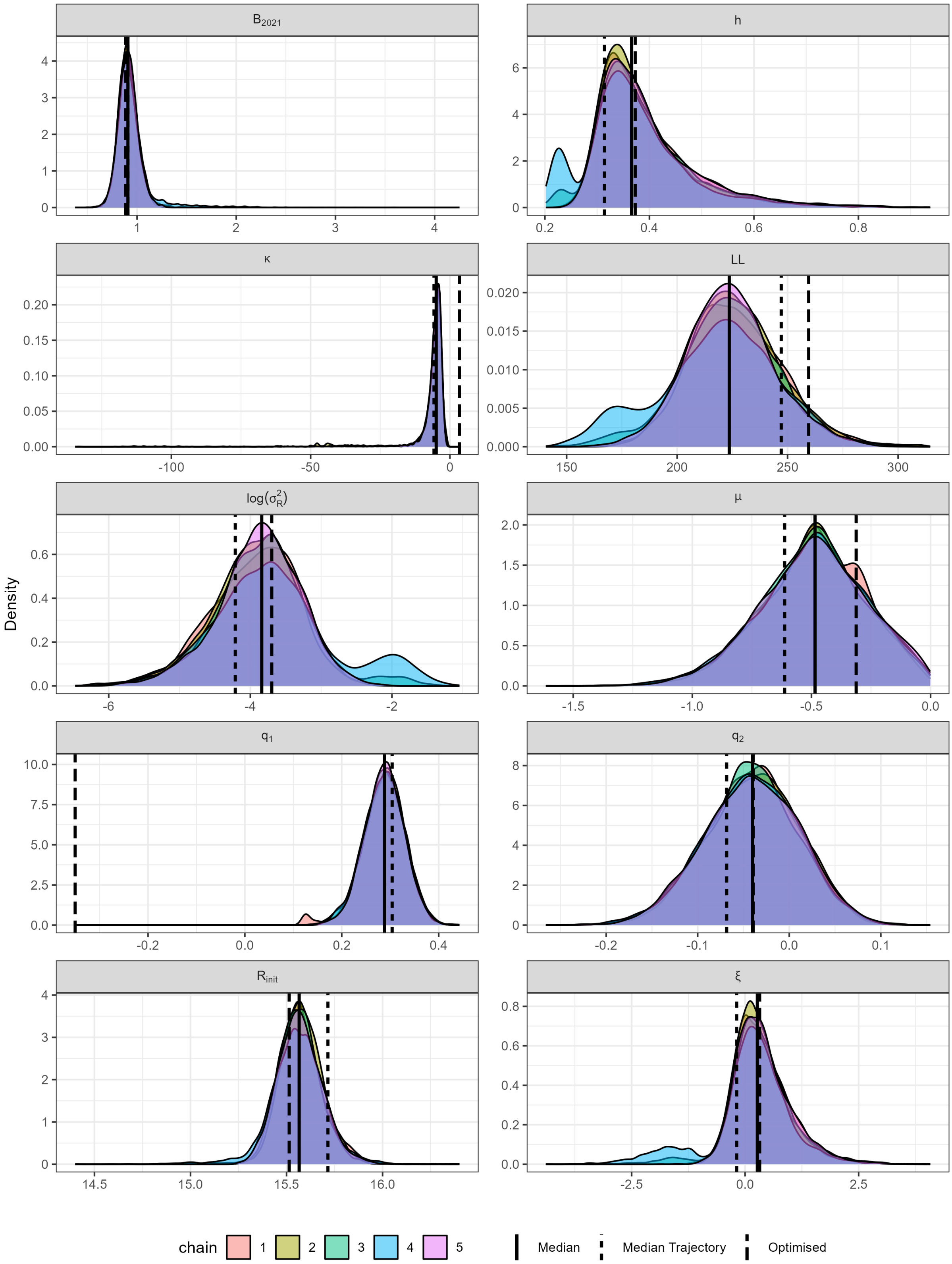


Figure B.19: Posterior density of MCMC chains for mud bugs scenario 6. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

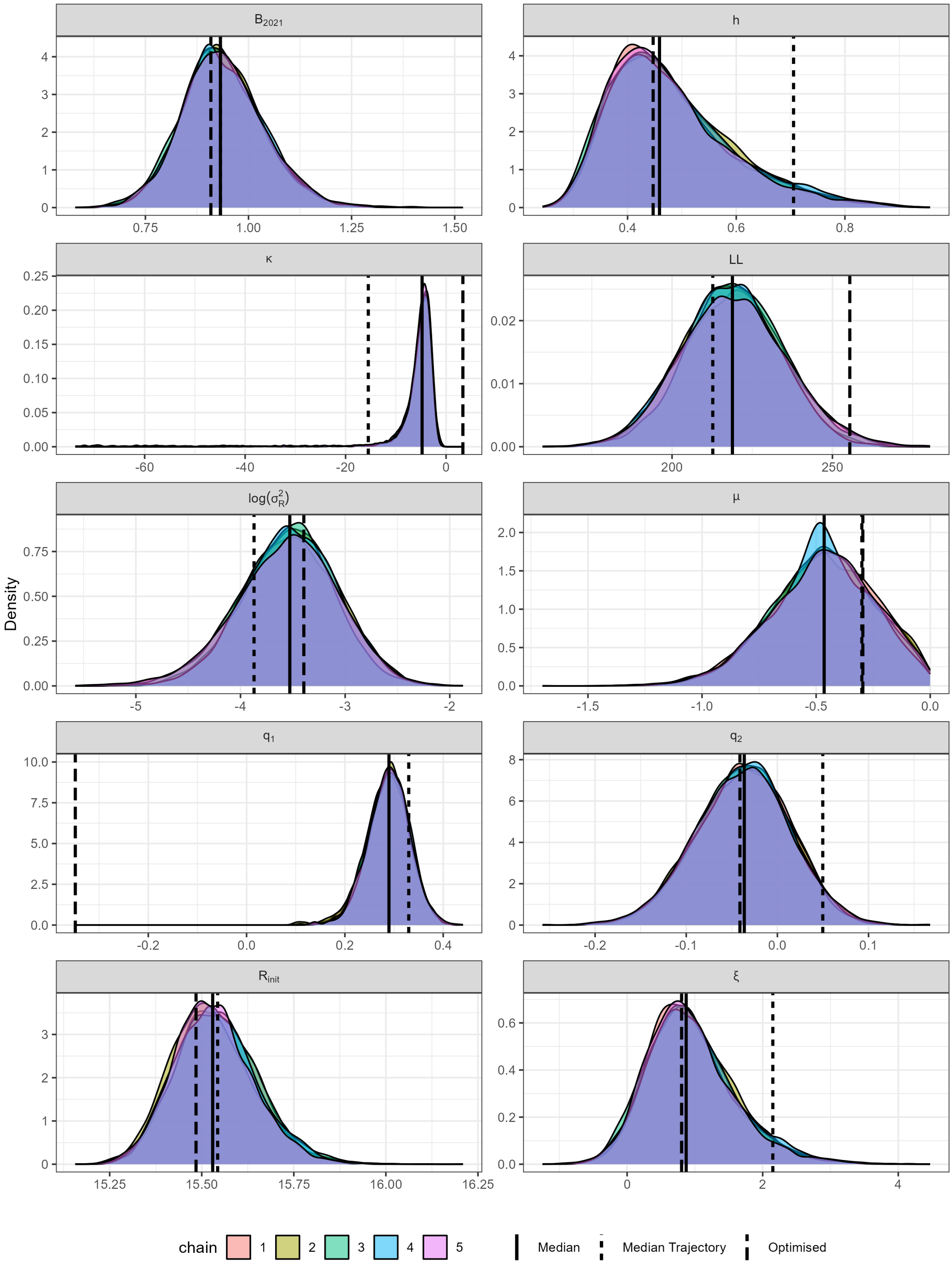


Figure B.20: Posterior density of MCMC chains for mud bugs scenario 7. ‘Median’ line shows median parameter value for MCMC chains. ‘Median Trajectory’ line shows parameter value for trajectory resulting in median biomass in 2021. ‘Optimised’ shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

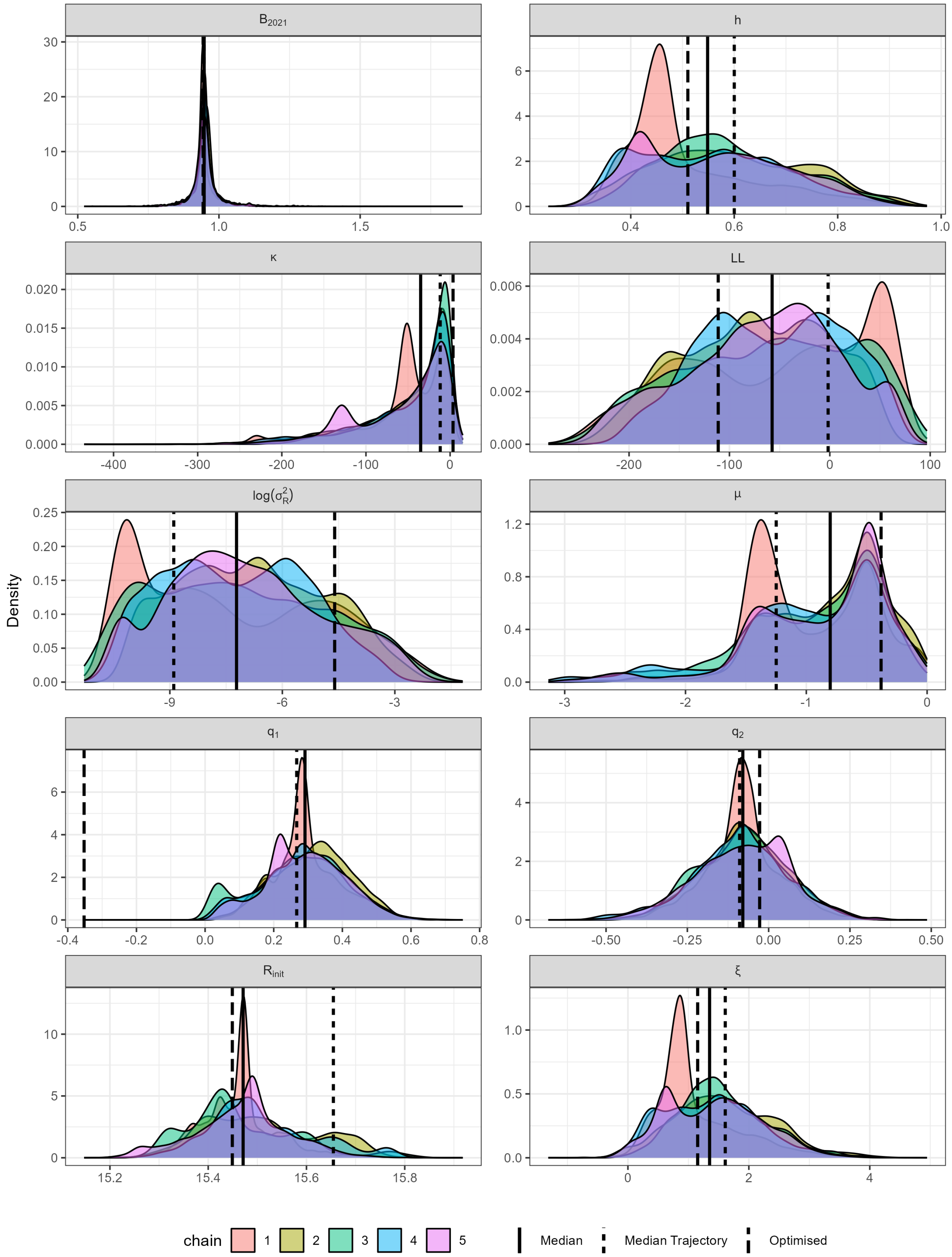


Figure B.21: Posterior density of MCMC chains for mud bugs scenario 8. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

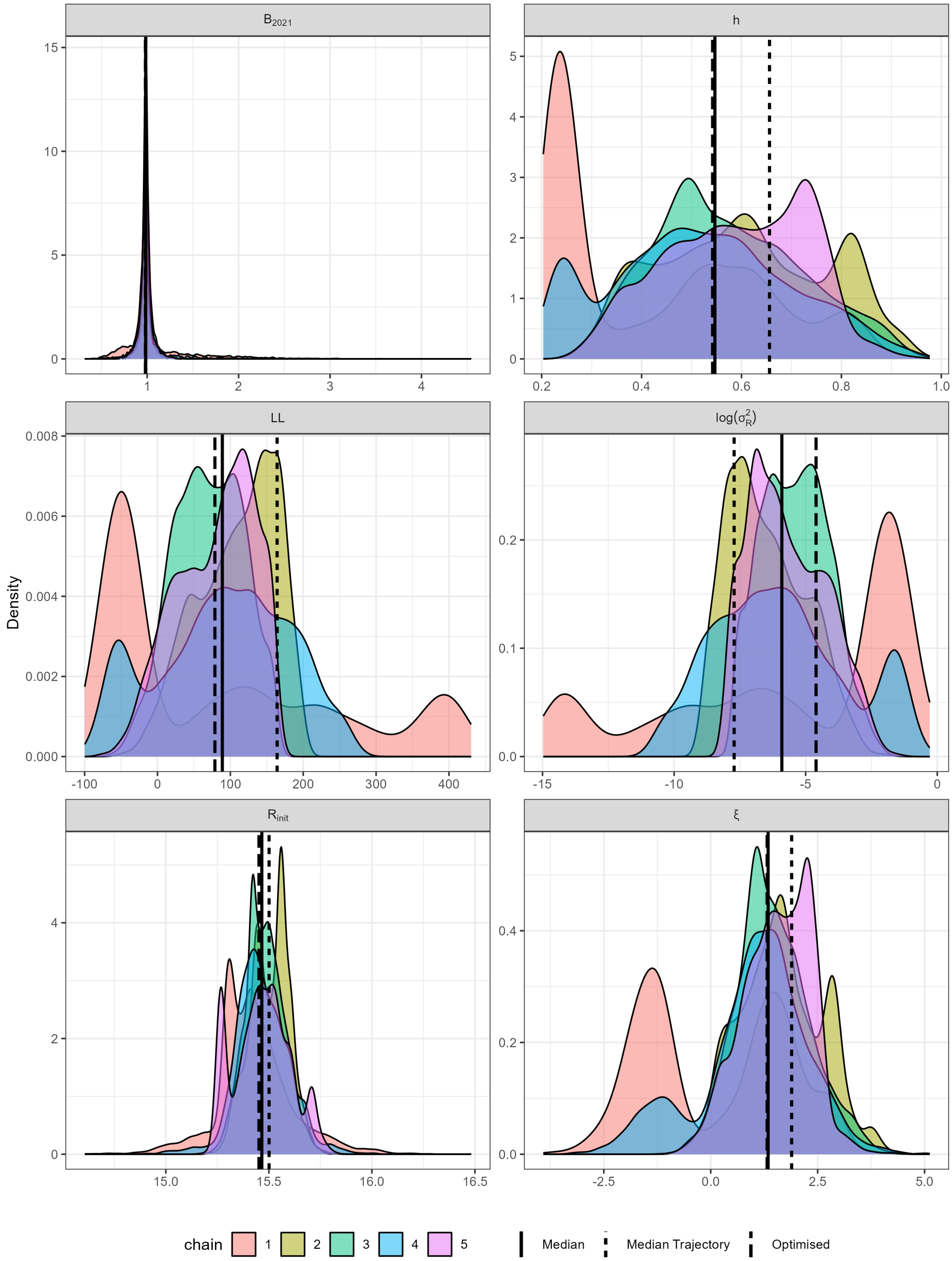


Figure B.22: Posterior density of MCMC chains for mud bugs scenario 9. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

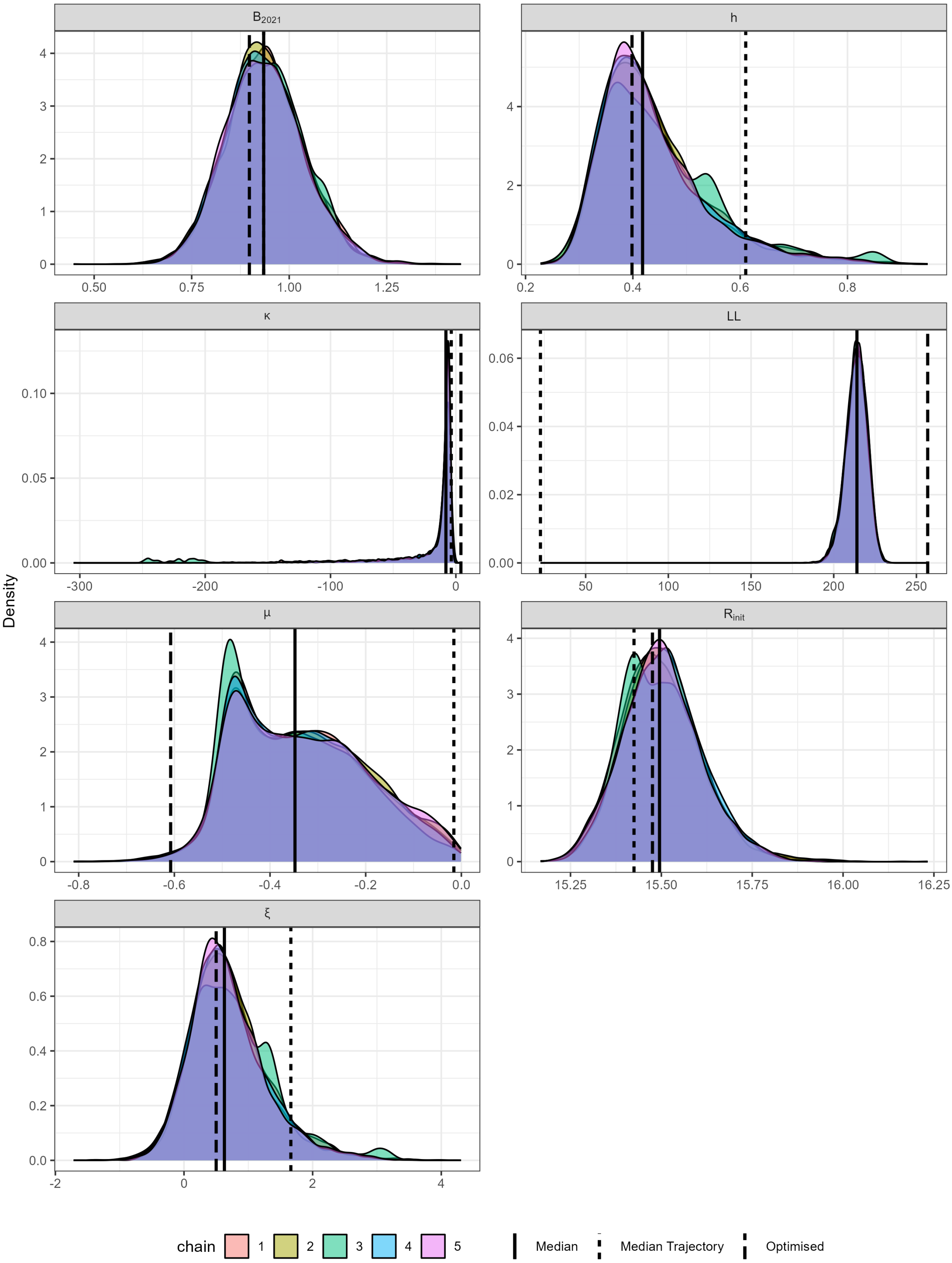


Figure B.23: Posterior density of MCMC chains for mud bugs scenario 10. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

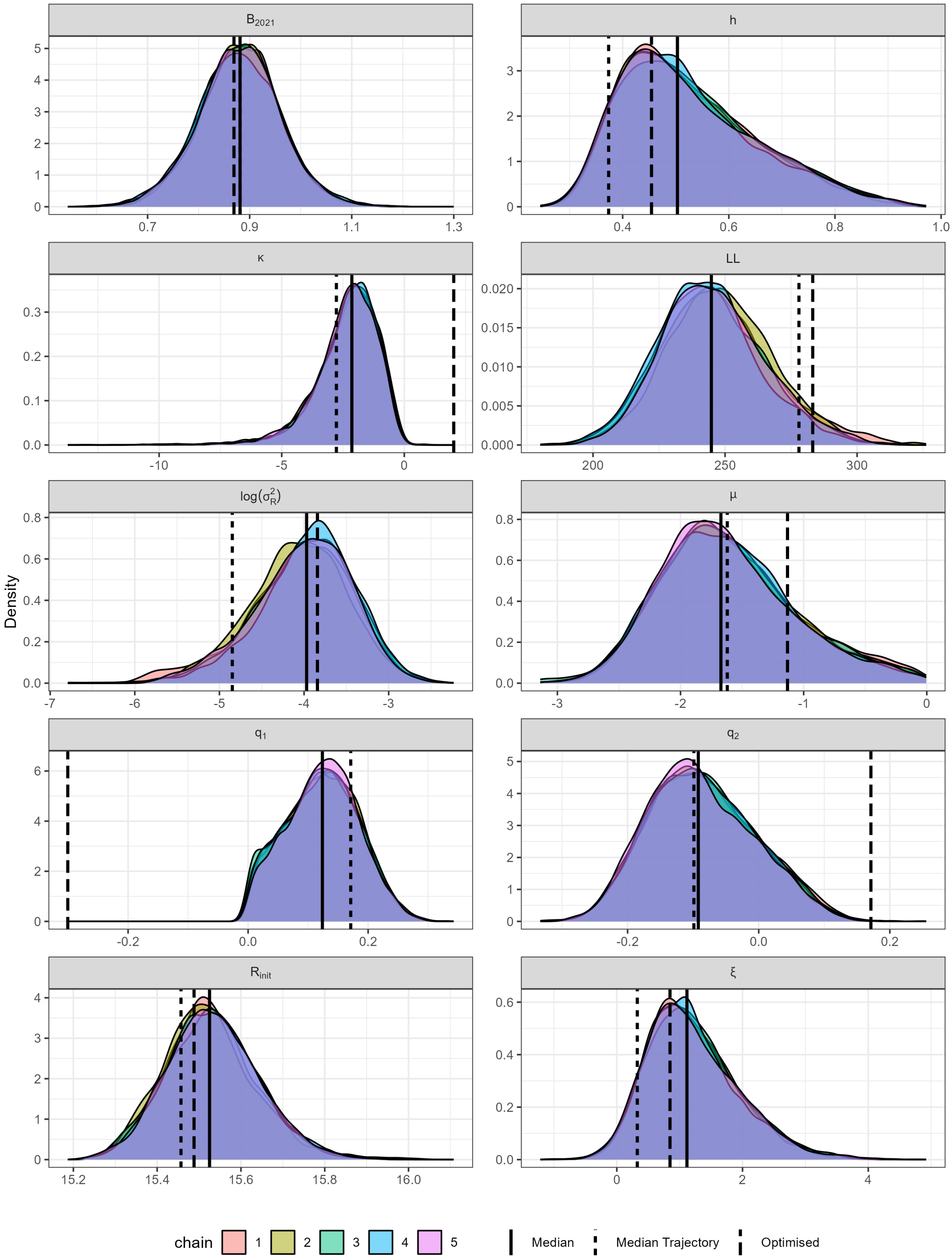


Figure B.24: Posterior density of MCMC chains for mud bugs scenario 11. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

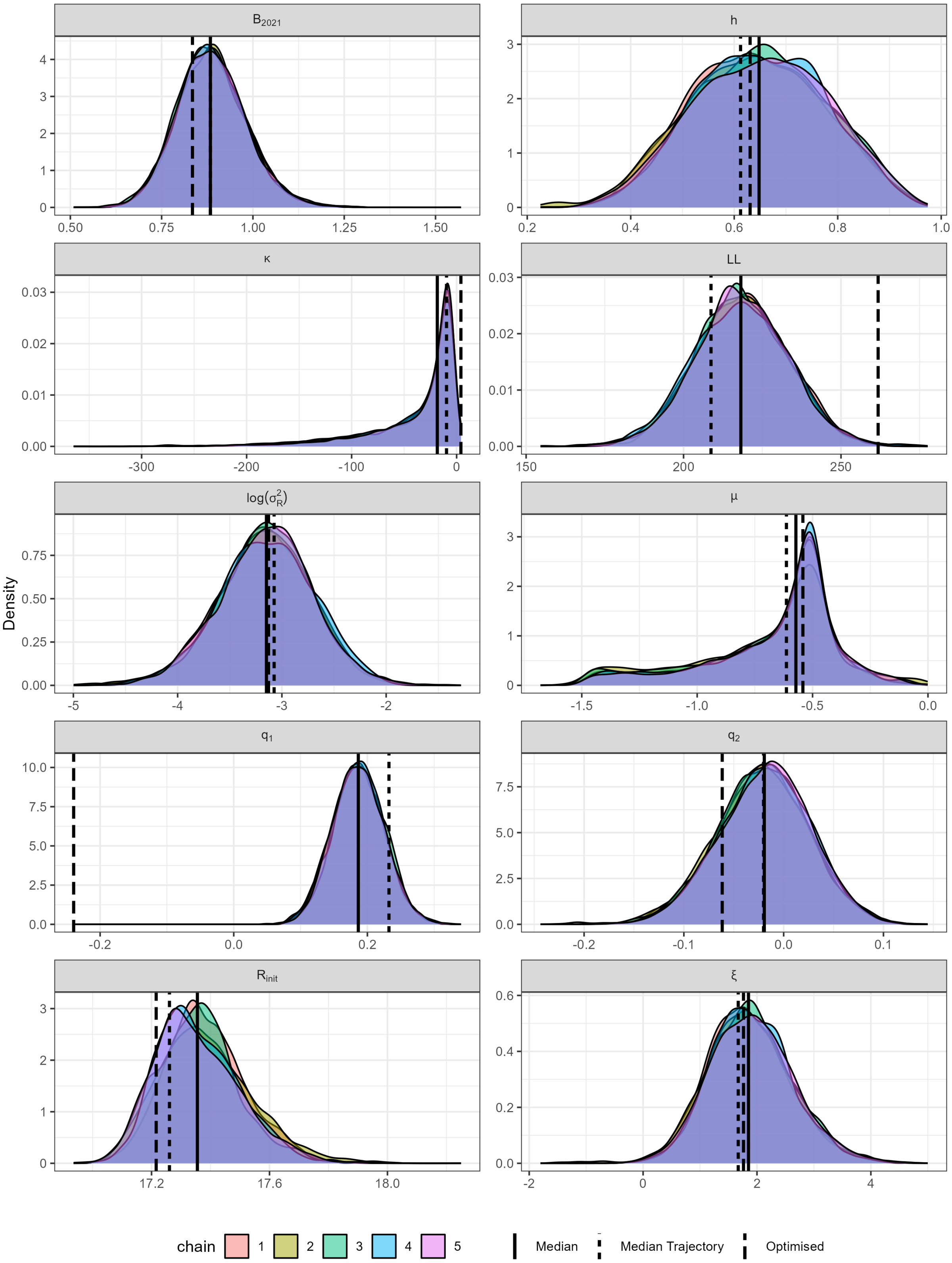


Figure B.25: Posterior density of MCMC chains for mud bugs scenario 12. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

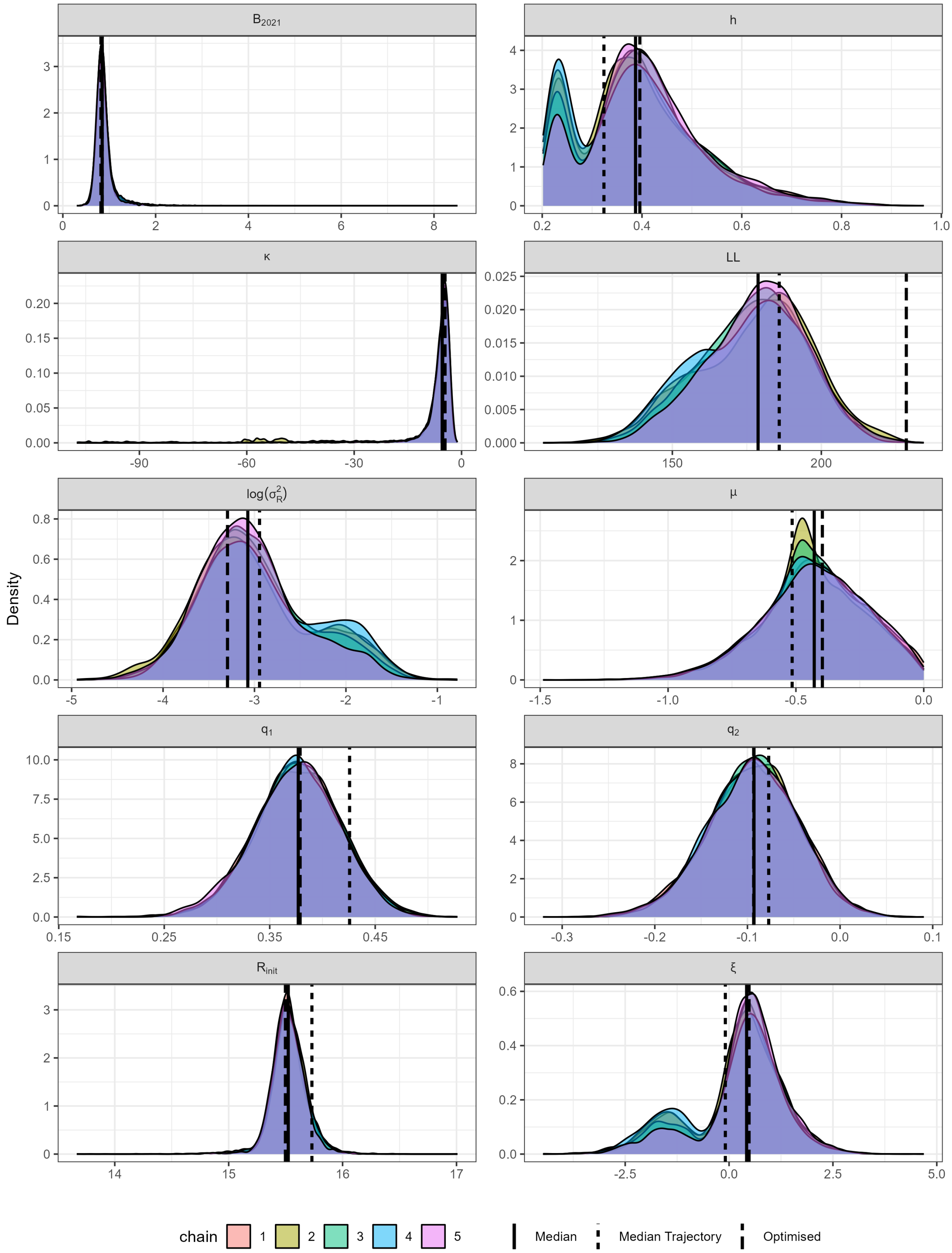


Figure B.26: Posterior density of MCMC chains for mud bugs scenario 13. 'Median' line shows median parameter value for MCMC chains. 'Median Trajectory' line shows parameter value for trajectory resulting in median biomass in 2021. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

B.1.2 Trace

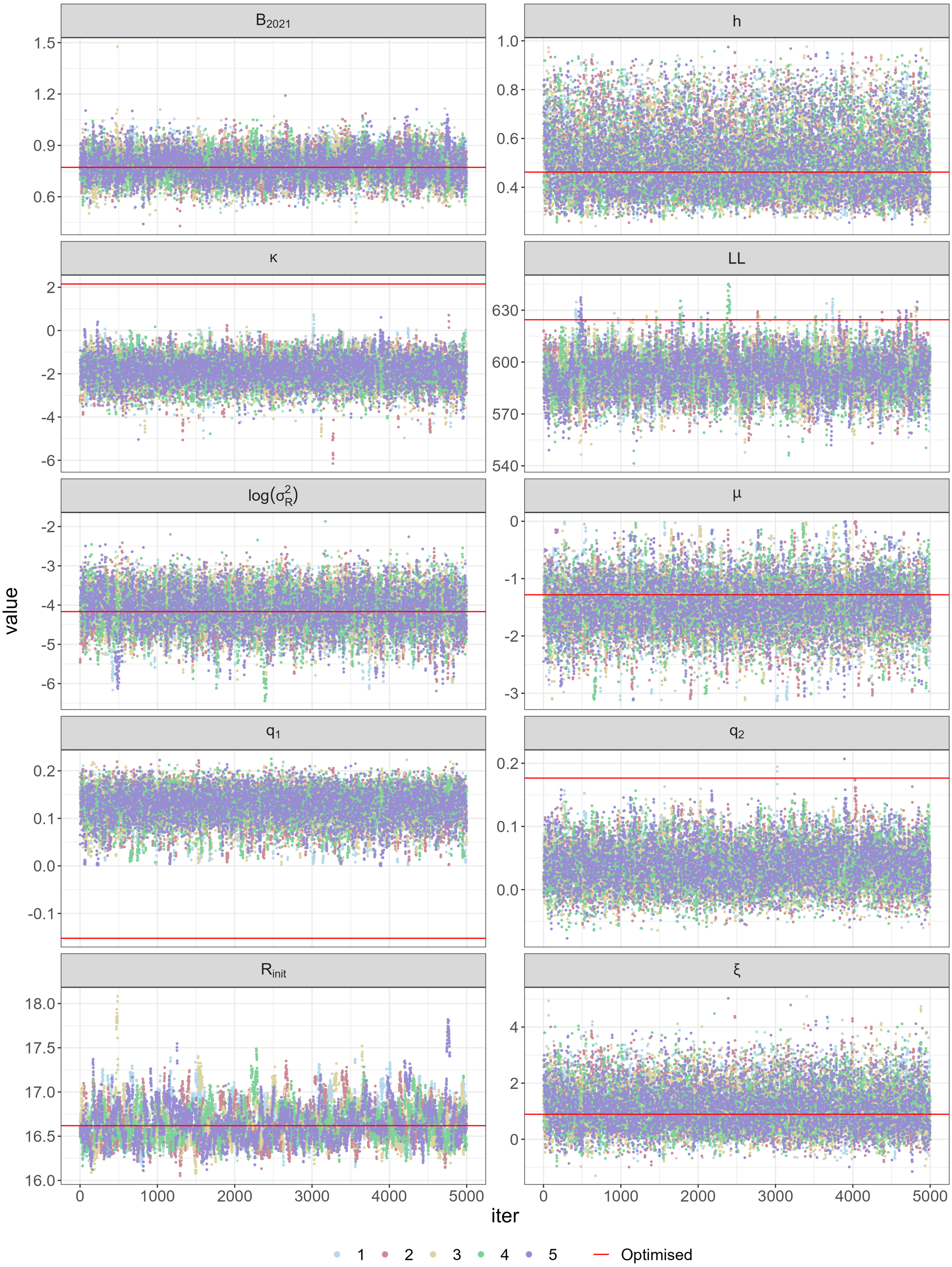


Figure B.27: Trace plot of MCMC chains for sand bugs scenario 1. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

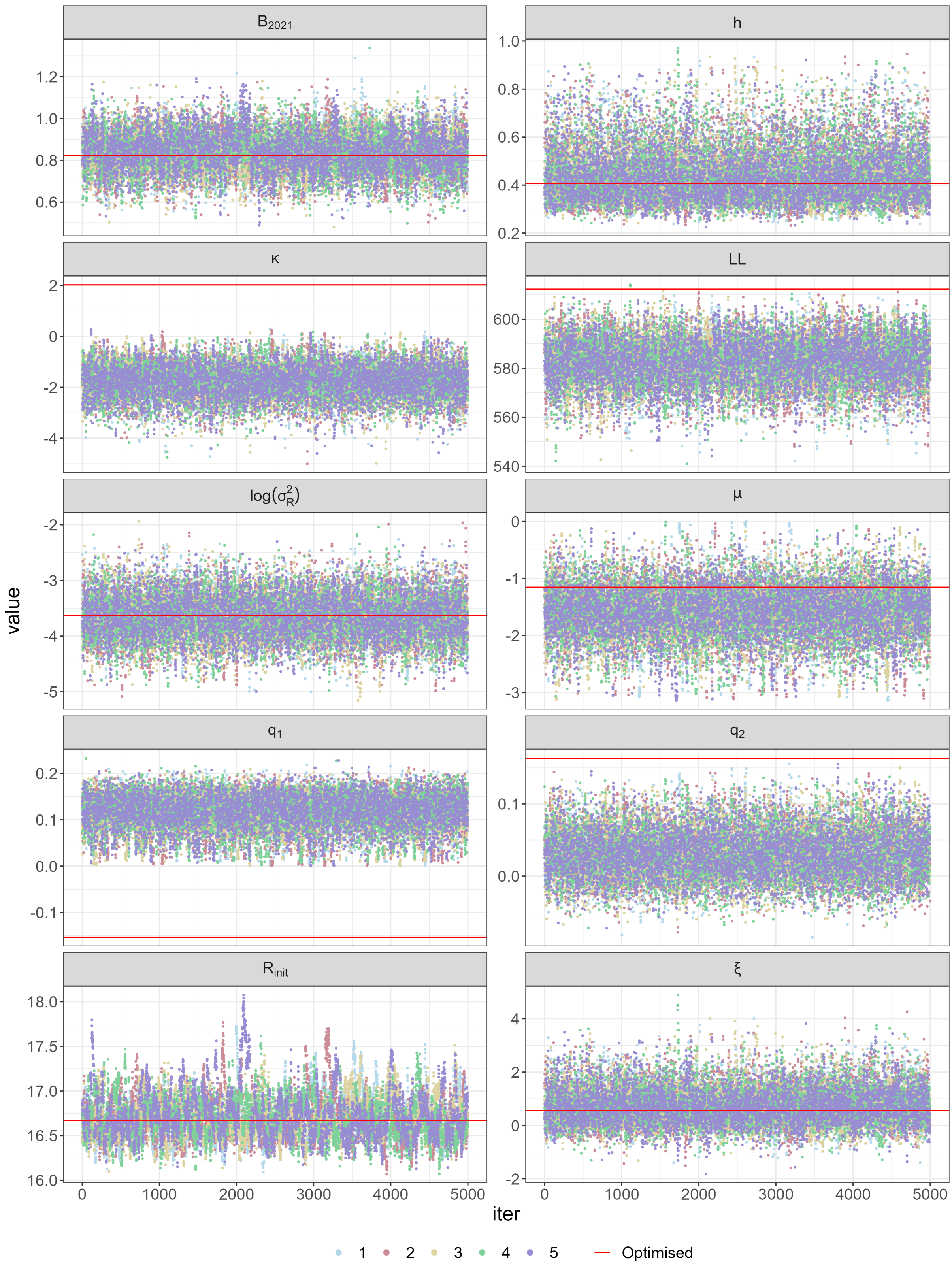


Figure B.28: Trace plot of MCMC chains for sand bugs scenario 2. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

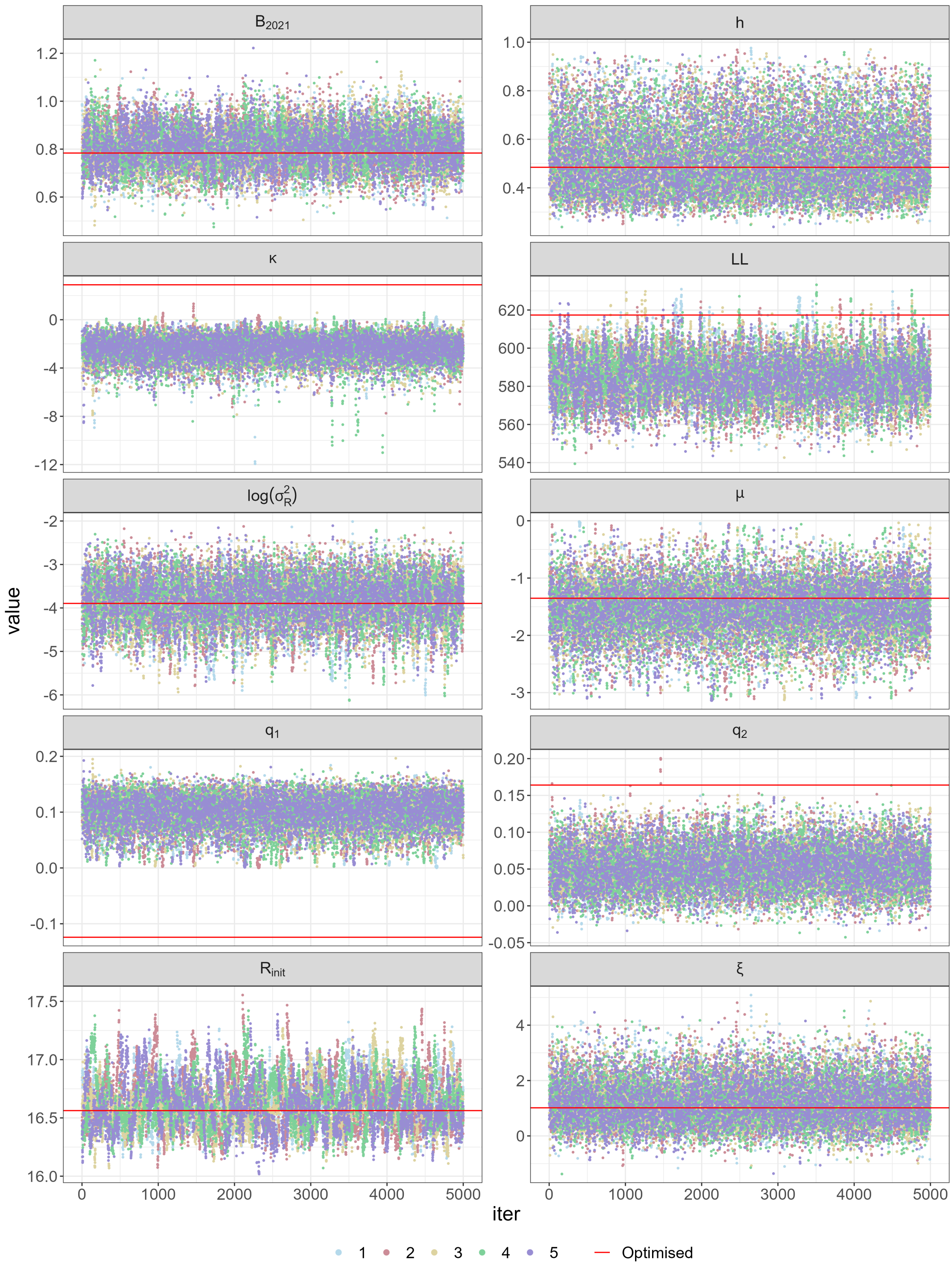


Figure B.29: Trace plot of MCMC chains for sand bugs scenario 3. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

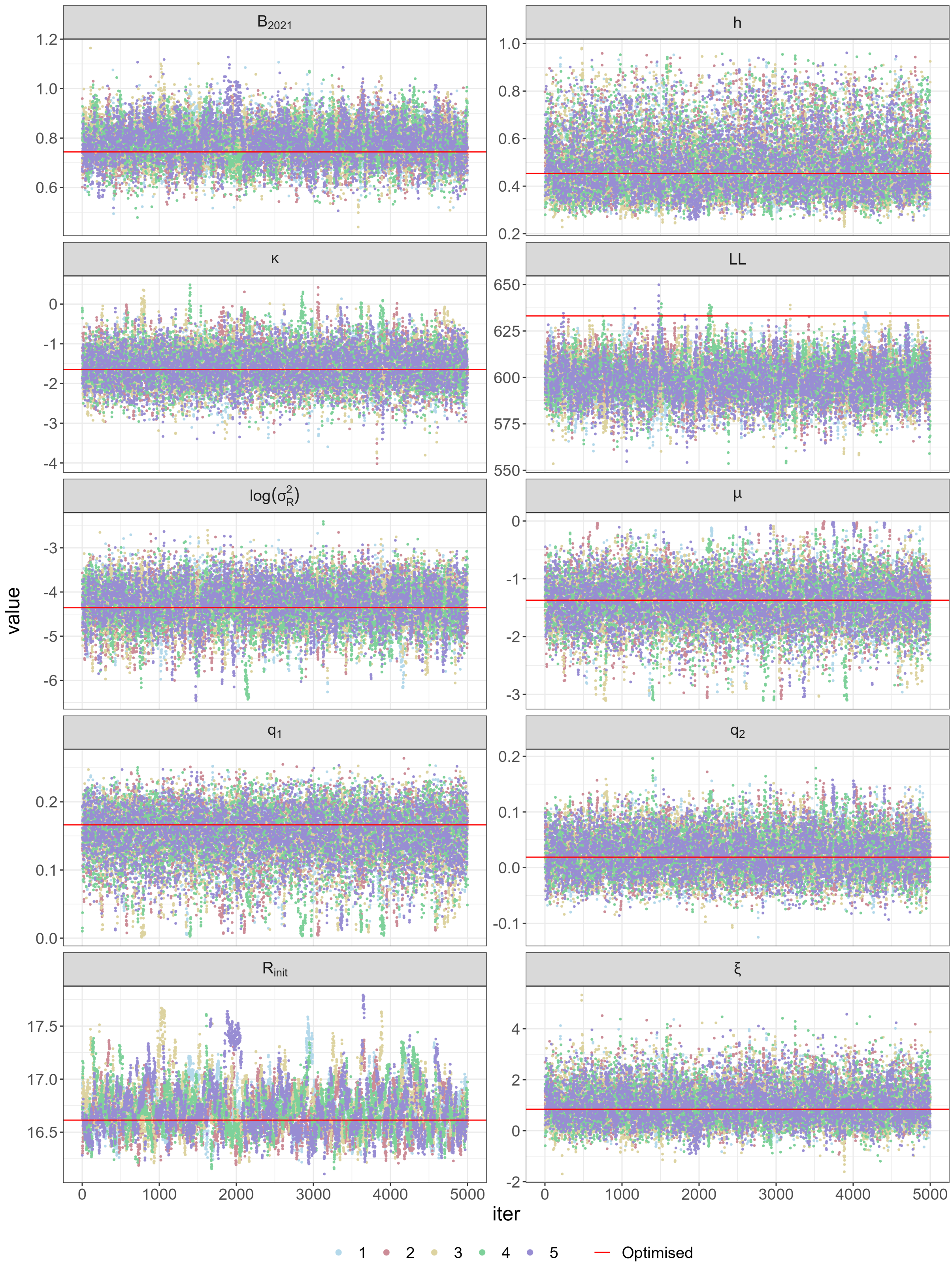


Figure B.30: Trace plot of MCMC chains for sand bugs scenario 4. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

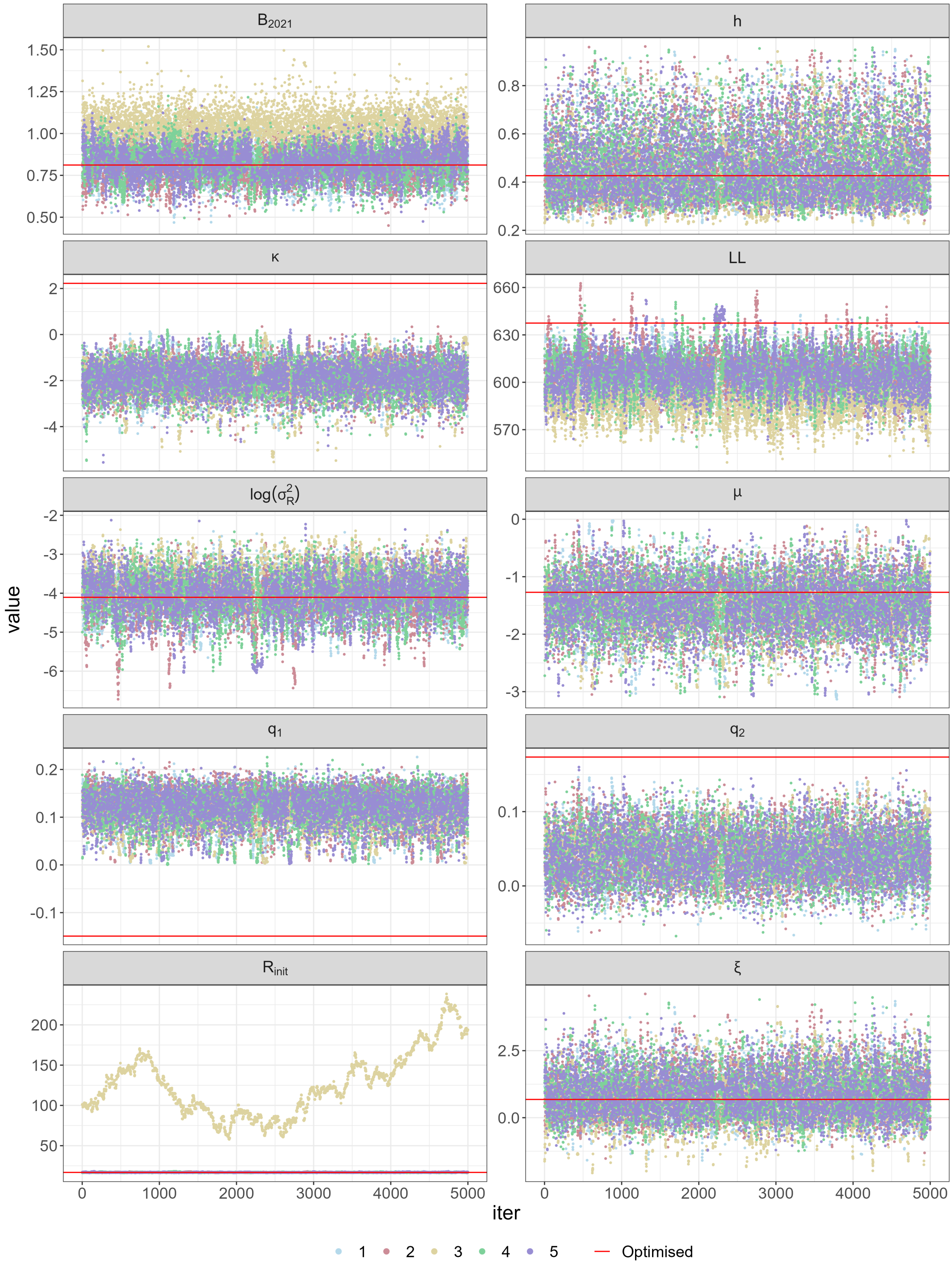


Figure B.31: Trace plot of MCMC chains for sand bugs scenario 5. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

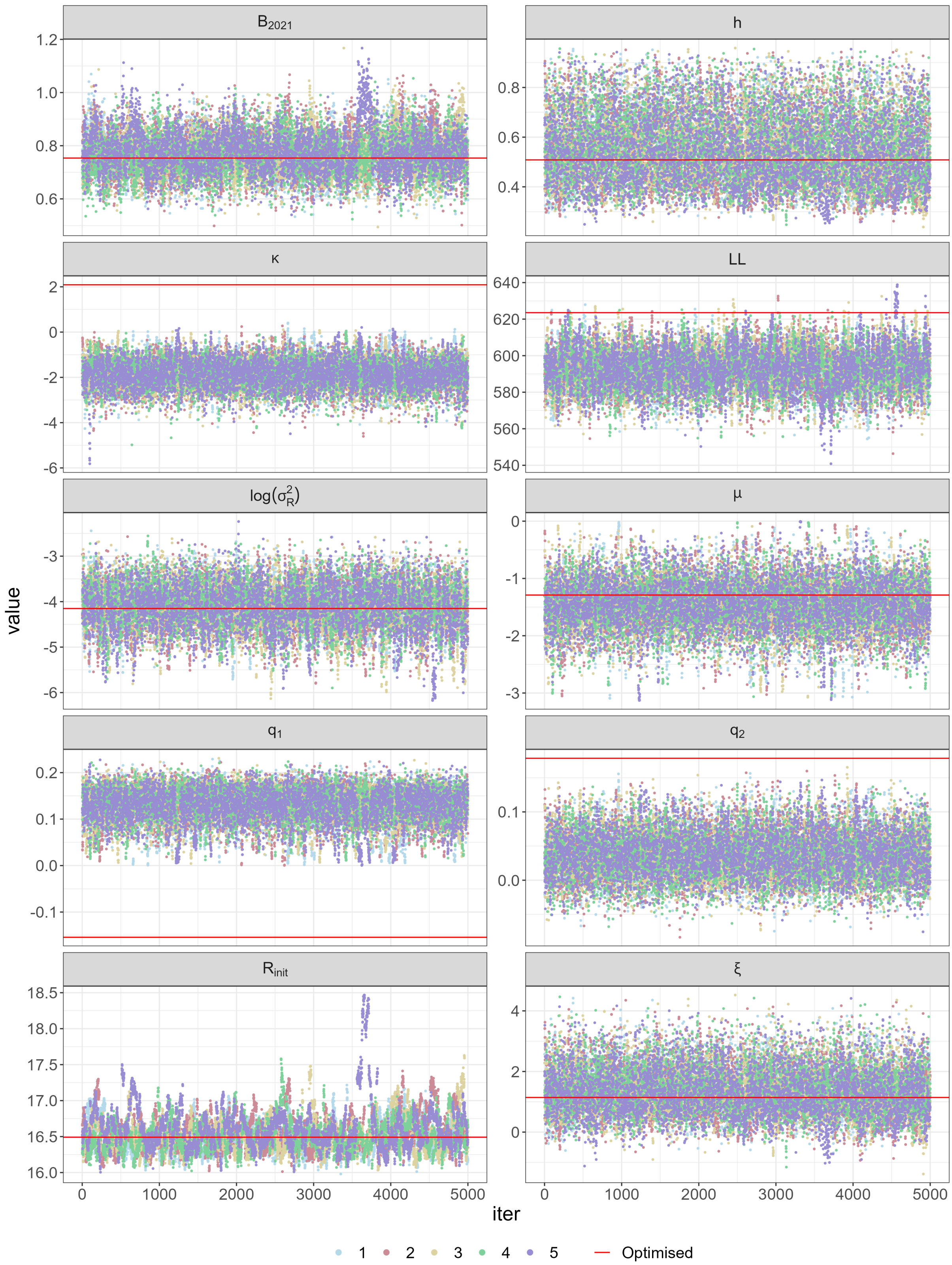


Figure B.32: Trace plot of MCMC chains for sand bugs scenario 6. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

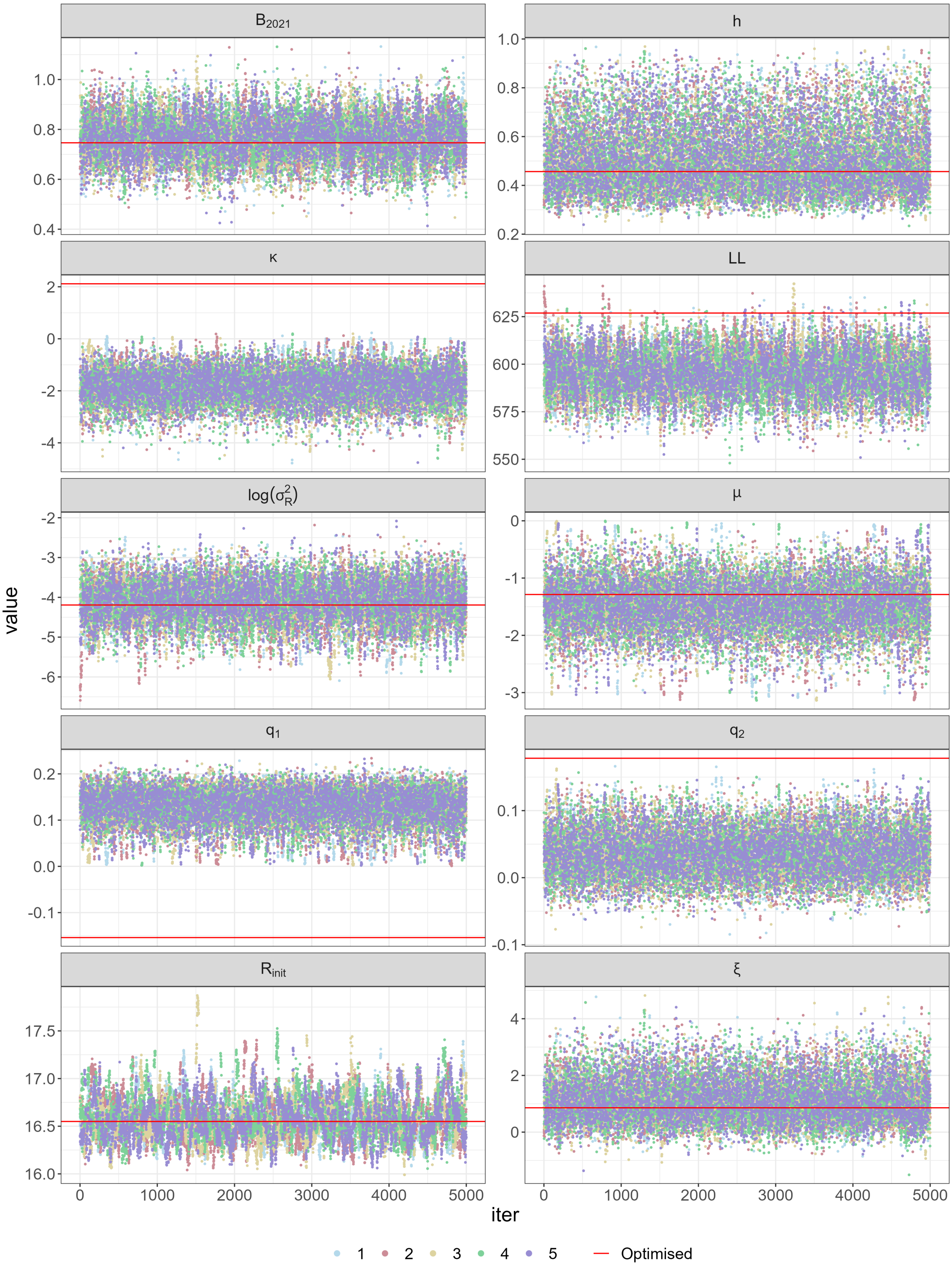


Figure B.33: Trace plot of MCMC chains for sand bugs scenario 7. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

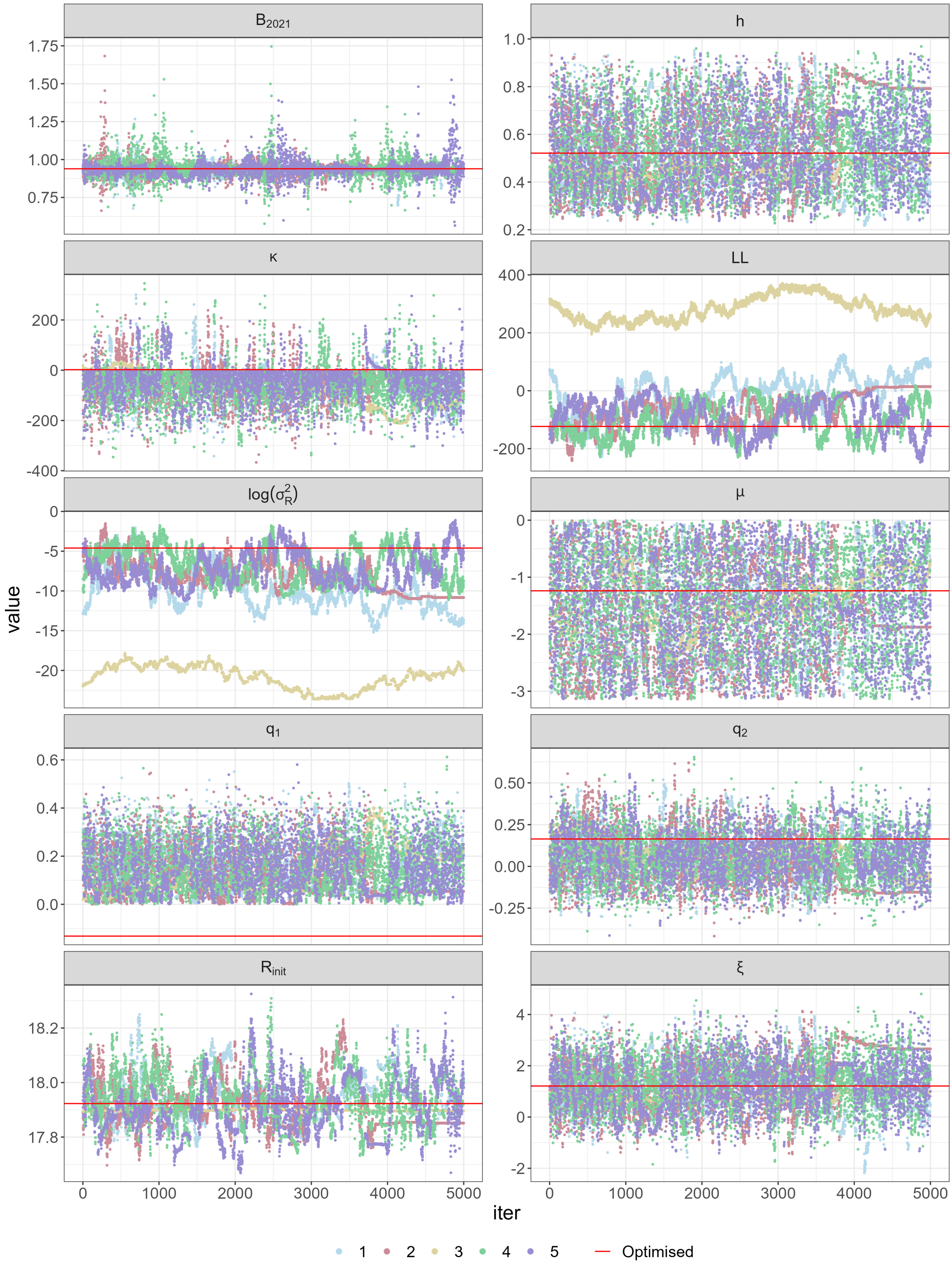


Figure B.34: Trace plot of MCMC chains for sand bugs scenario 8. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

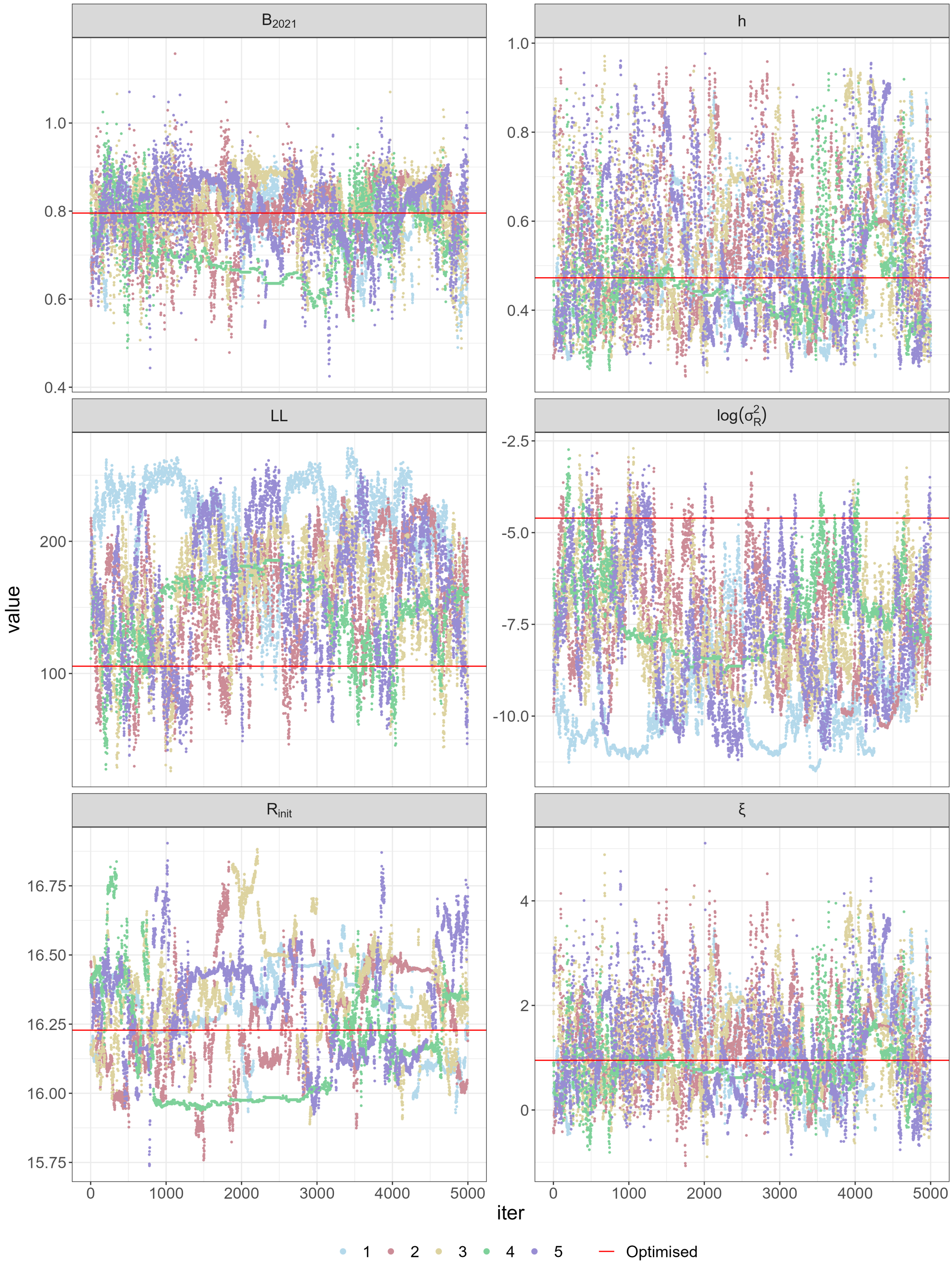


Figure B.35: Trace plot of MCMC chains for sand bugs scenario 9. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

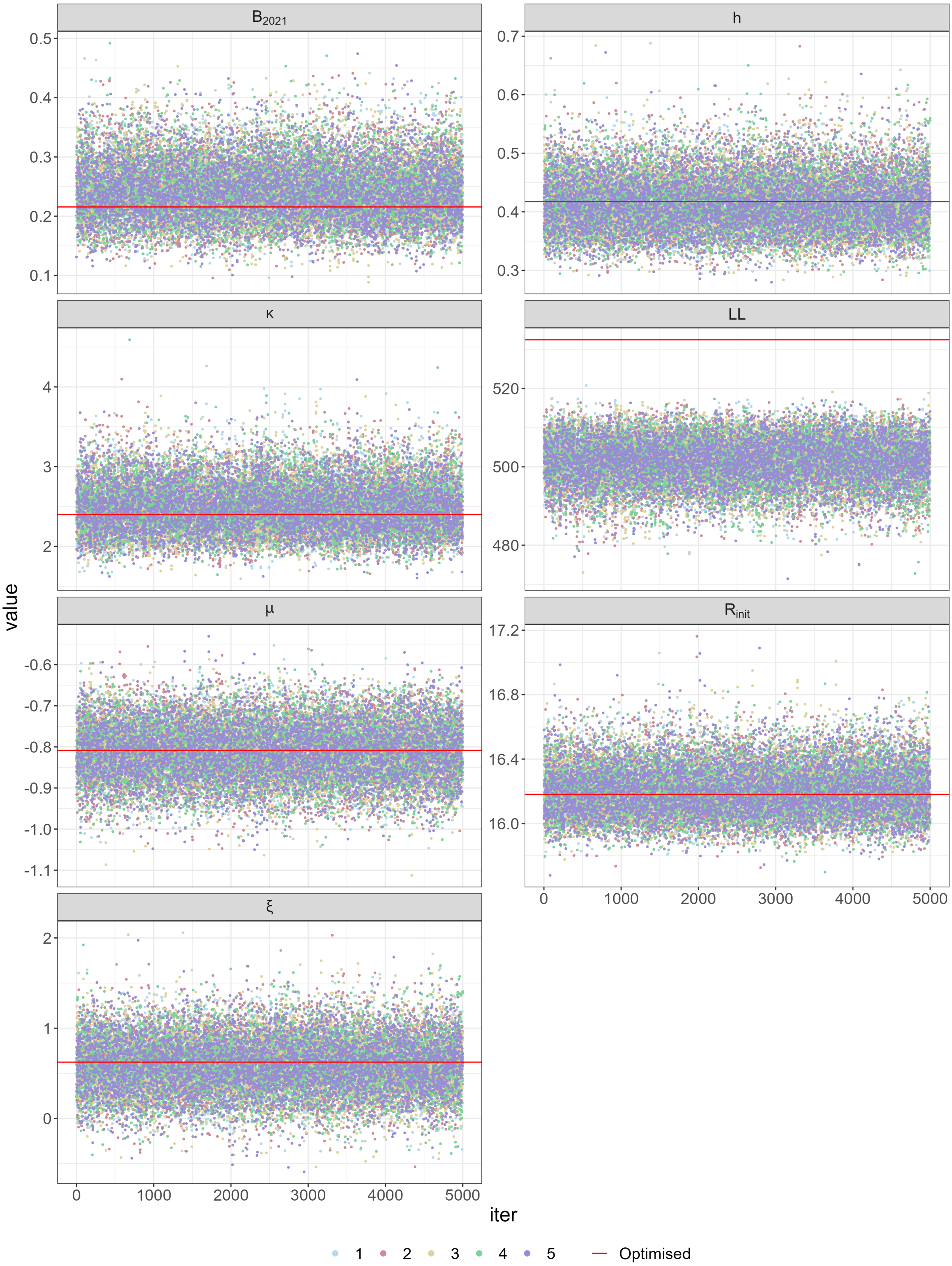


Figure B.36: Trace plot of MCMC chains for sand bugs scenario 10. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

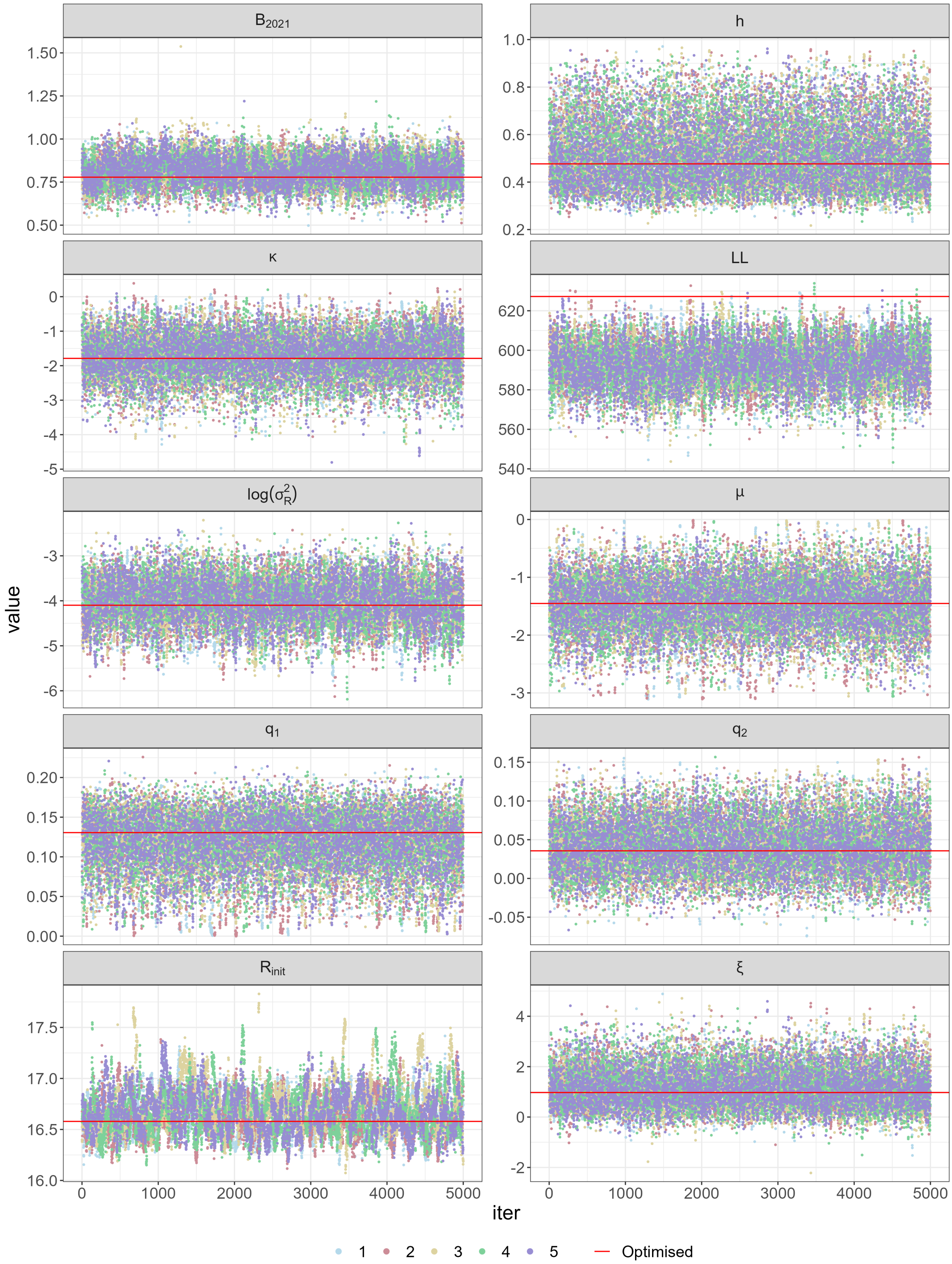


Figure B.37: Trace plot of MCMC chains for sand bugs scenario 11. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

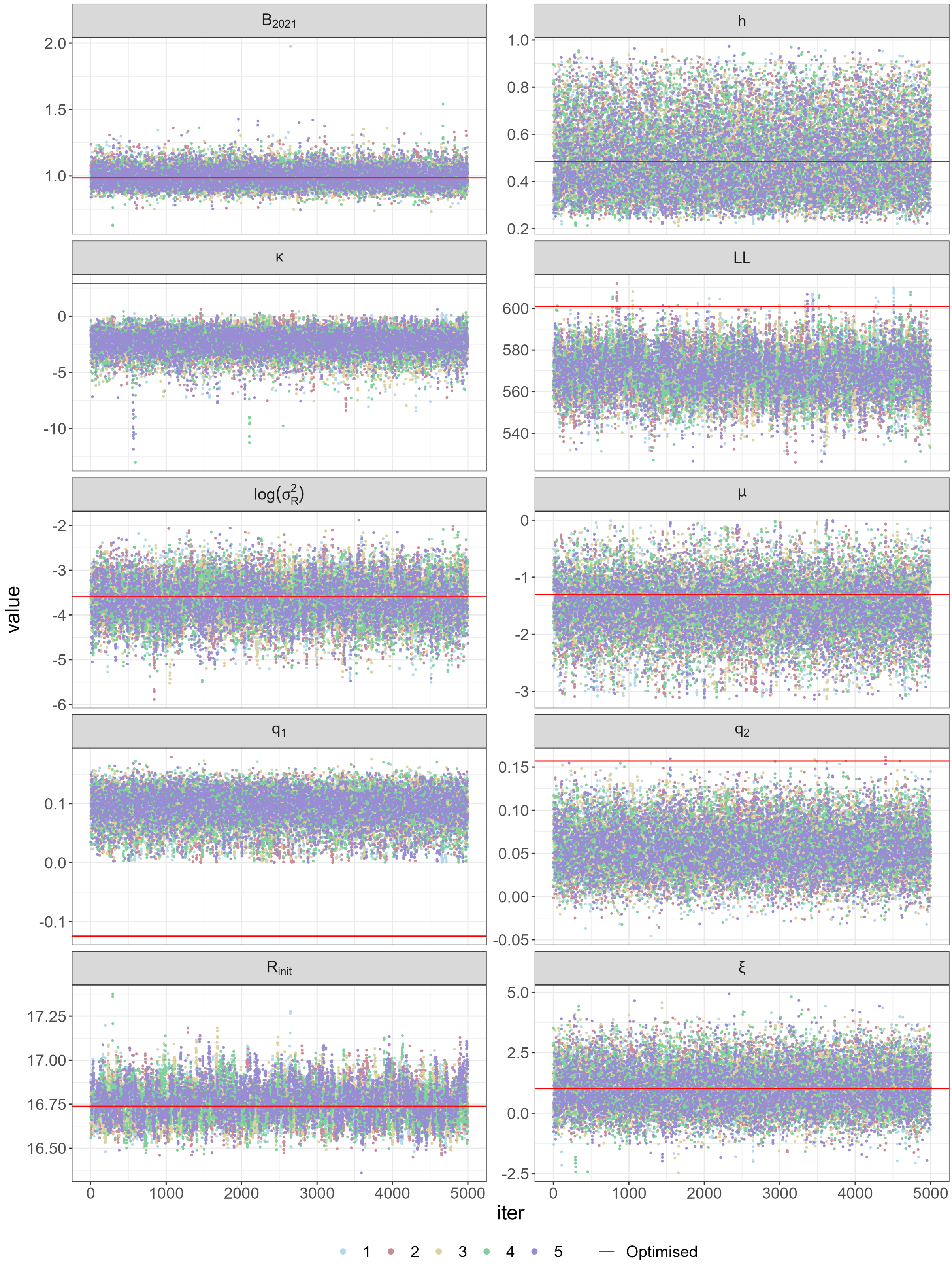


Figure B.38: Trace plot of MCMC chains for sand bugs scenario 12. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

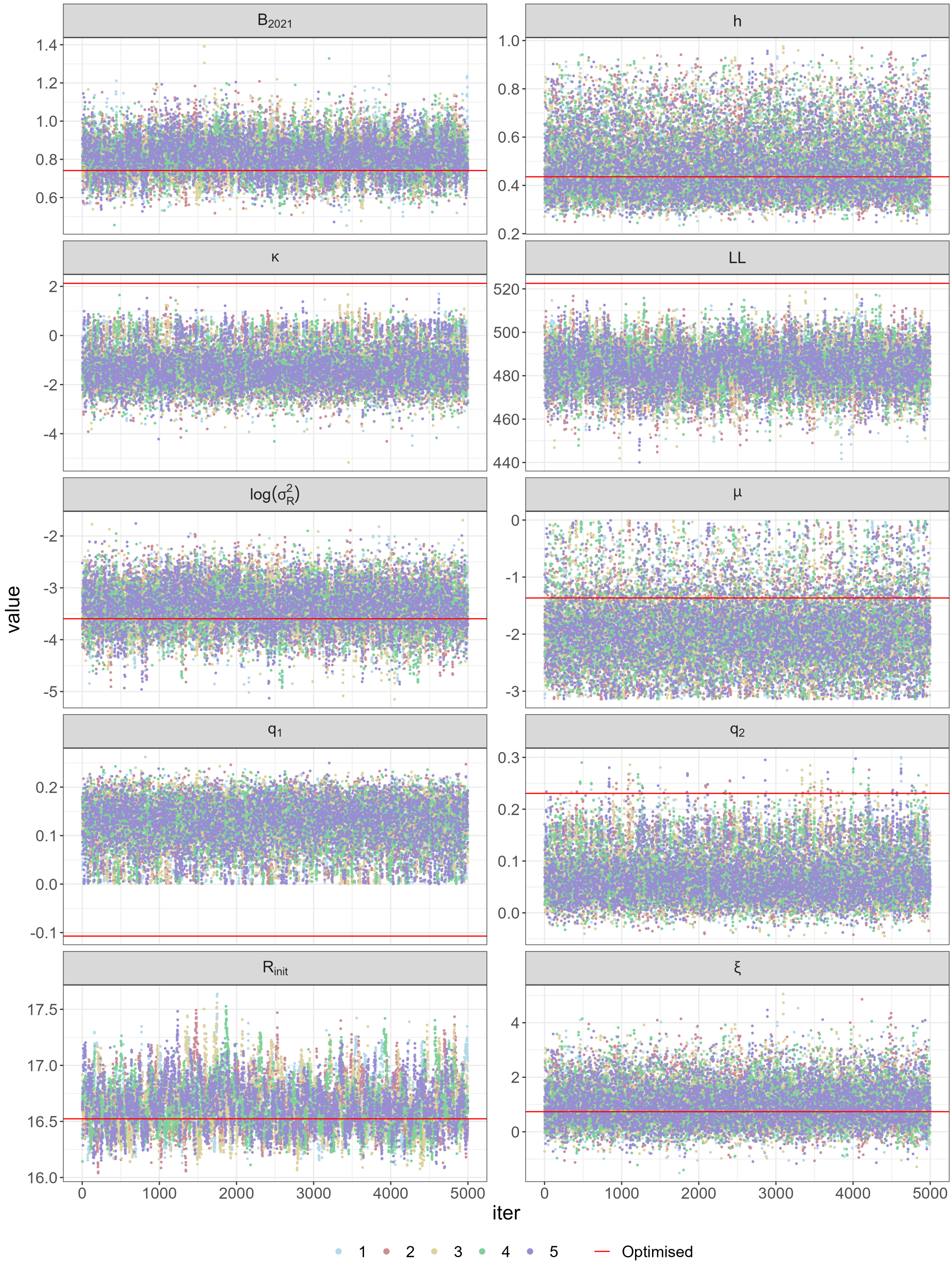


Figure B.39: Trace plot of MCMC chains for sand bugs scenario 13. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

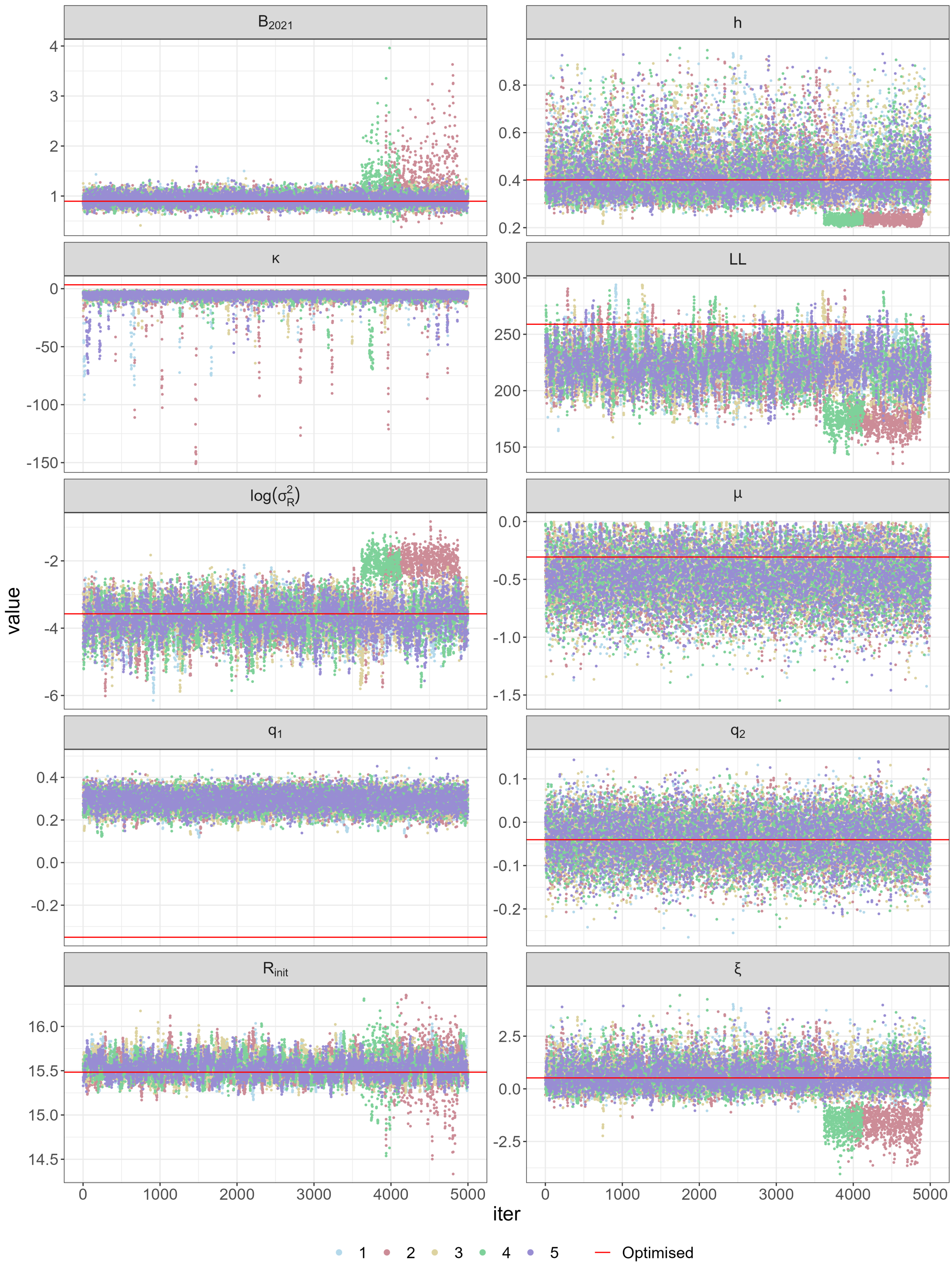


Figure B.40: Trace plot of MCMC chains for mud bugs scenario 1. ‘Optimised’ shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

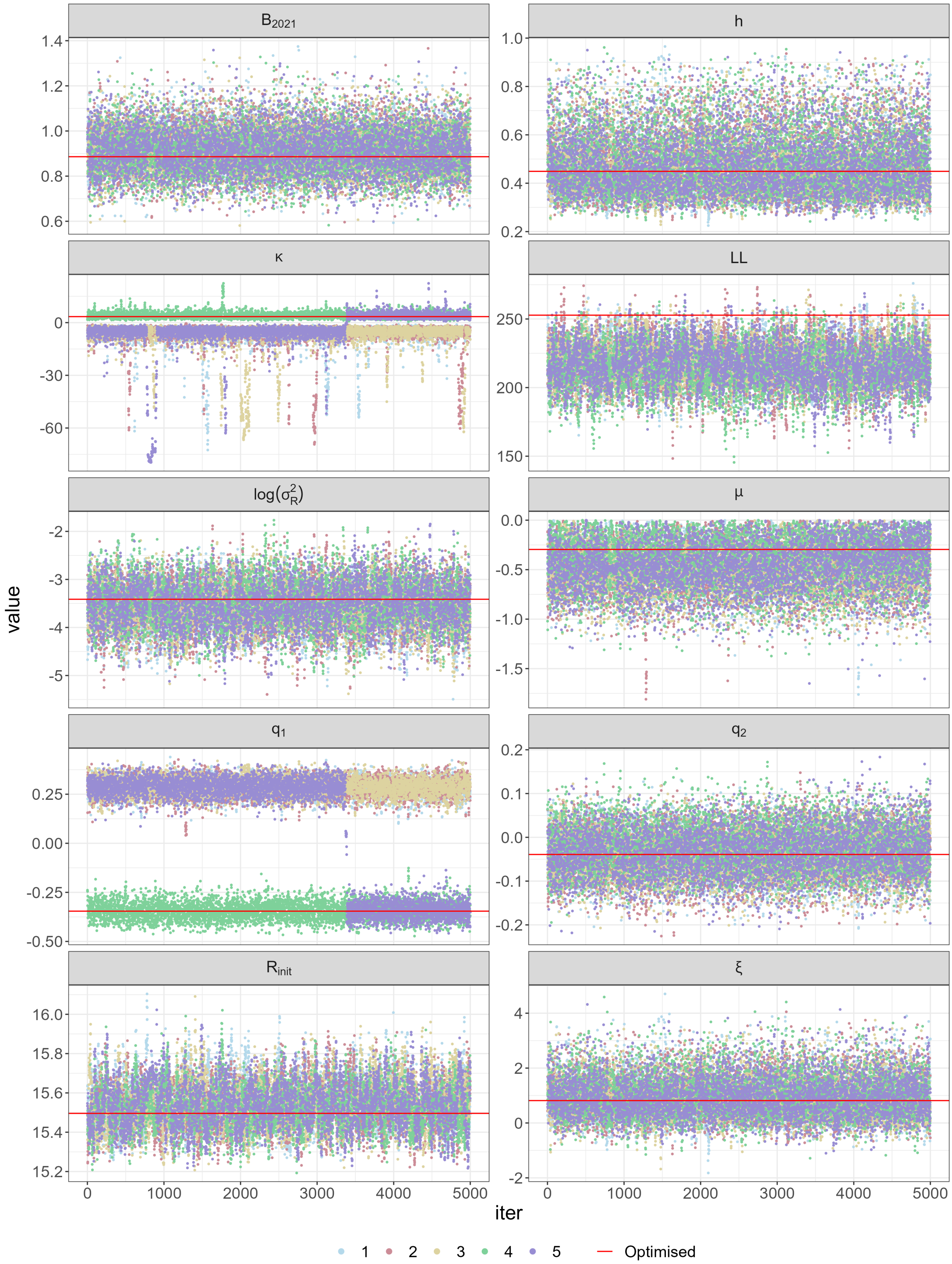


Figure B.41: Trace plot of MCMC chains for mud bugs scenario 2. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

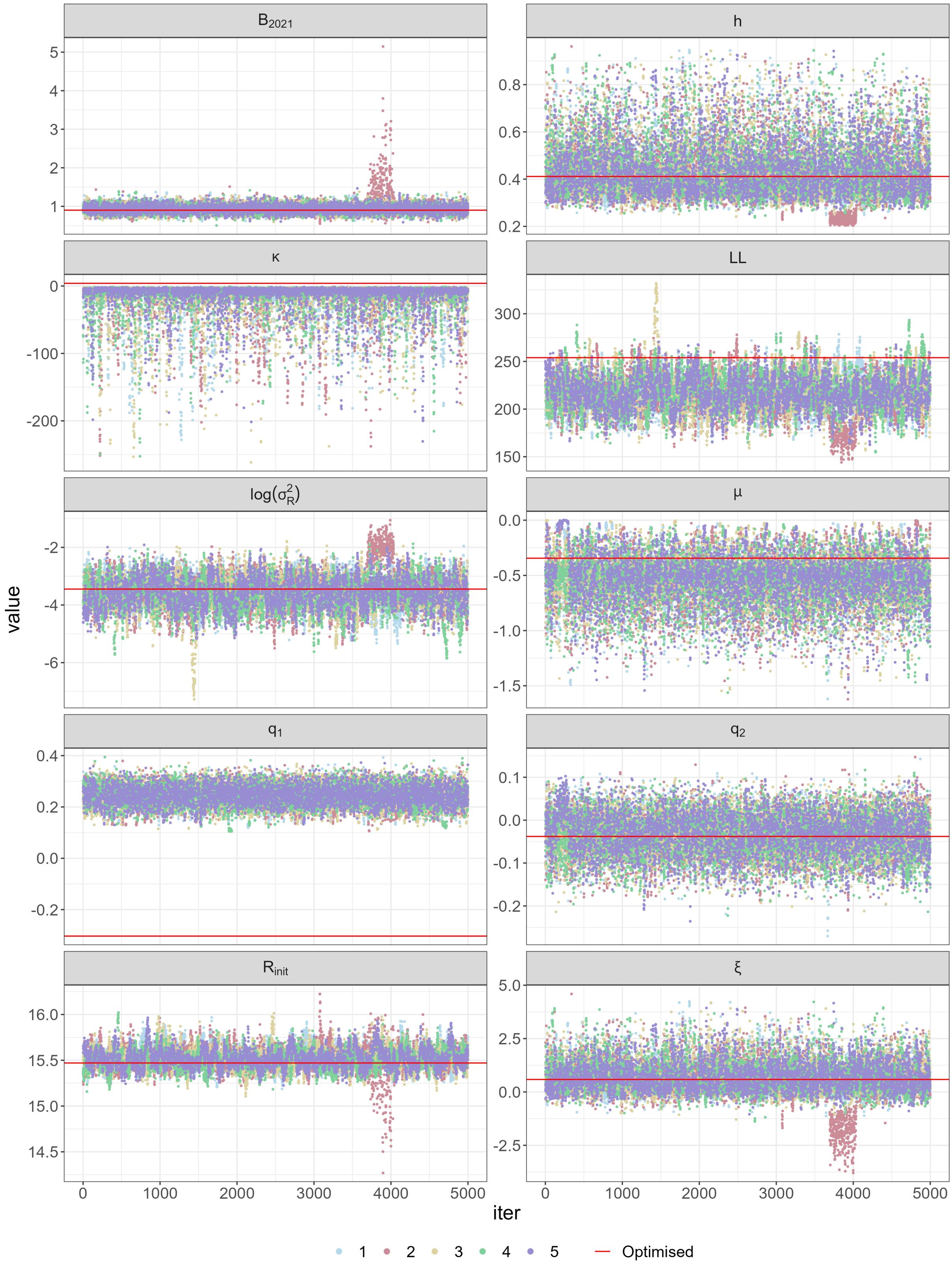


Figure B.42: Trace plot of MCMC chains for mud bugs scenario 3. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

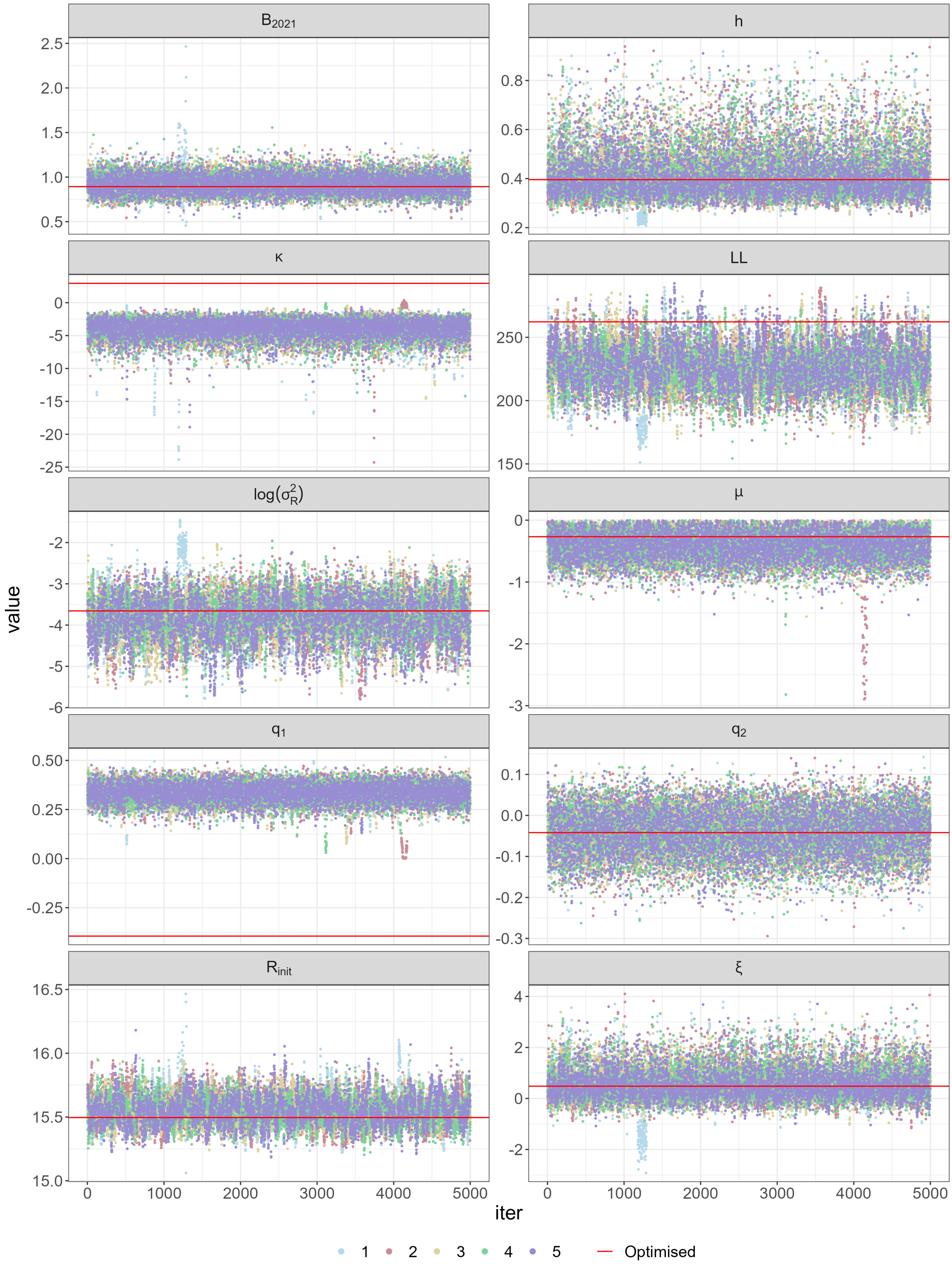


Figure B.43: Trace plot of MCMC chains for mud bugs scenario 4. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

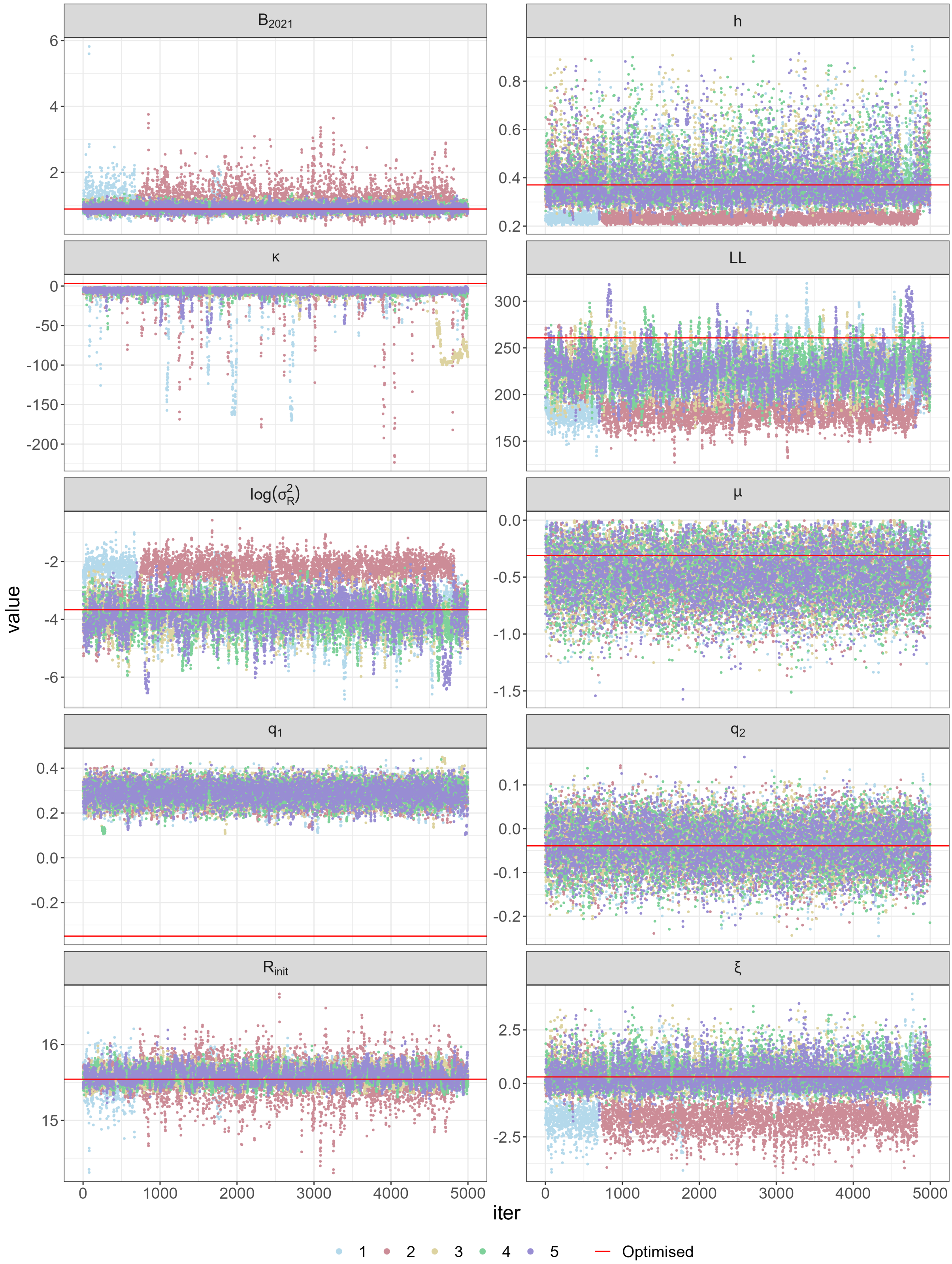


Figure B.44: Trace plot of MCMC chains for mud bugs scenario 5. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

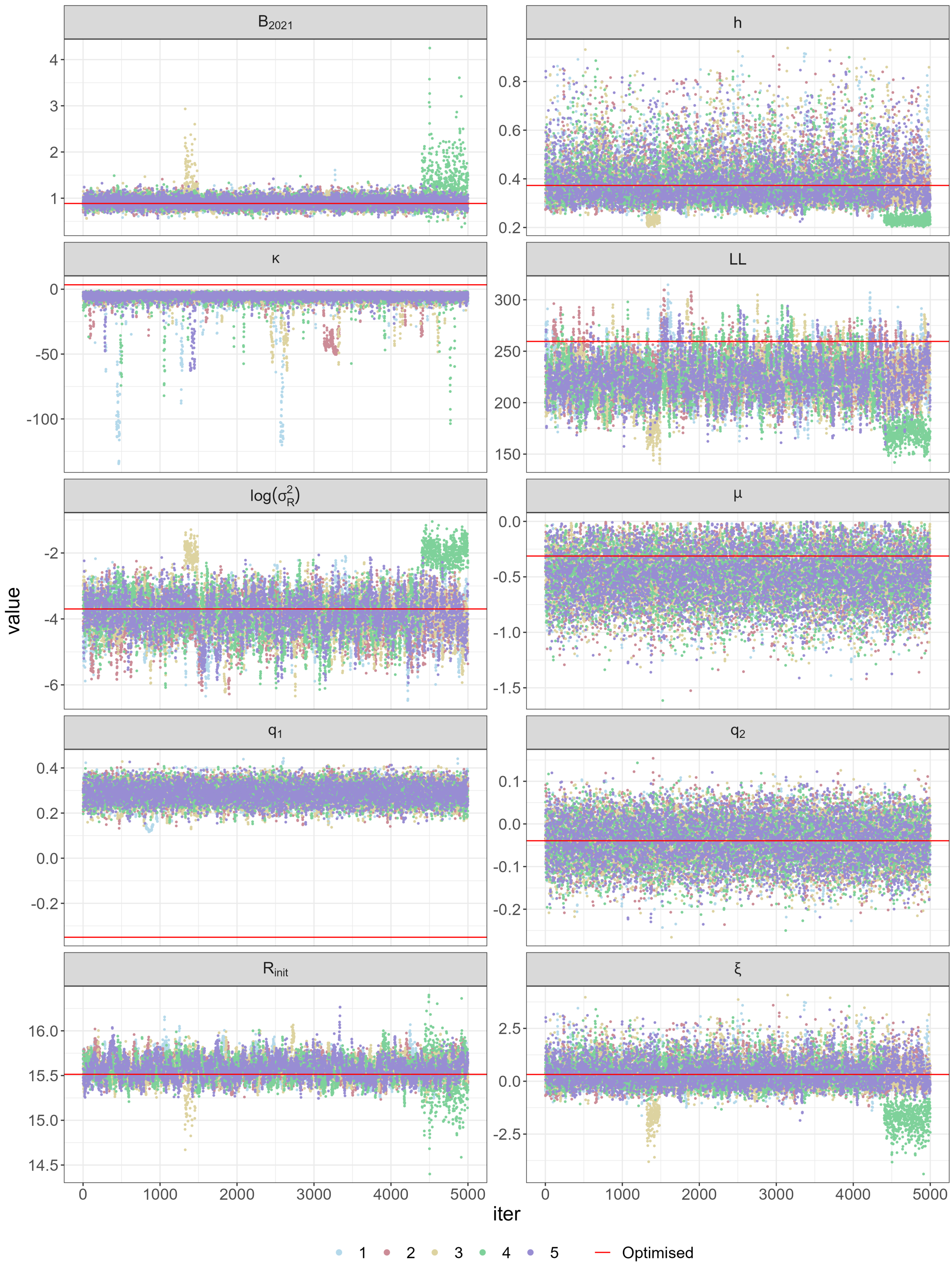


Figure B.45: Trace plot of MCMC chains for mud bugs scenario 6. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

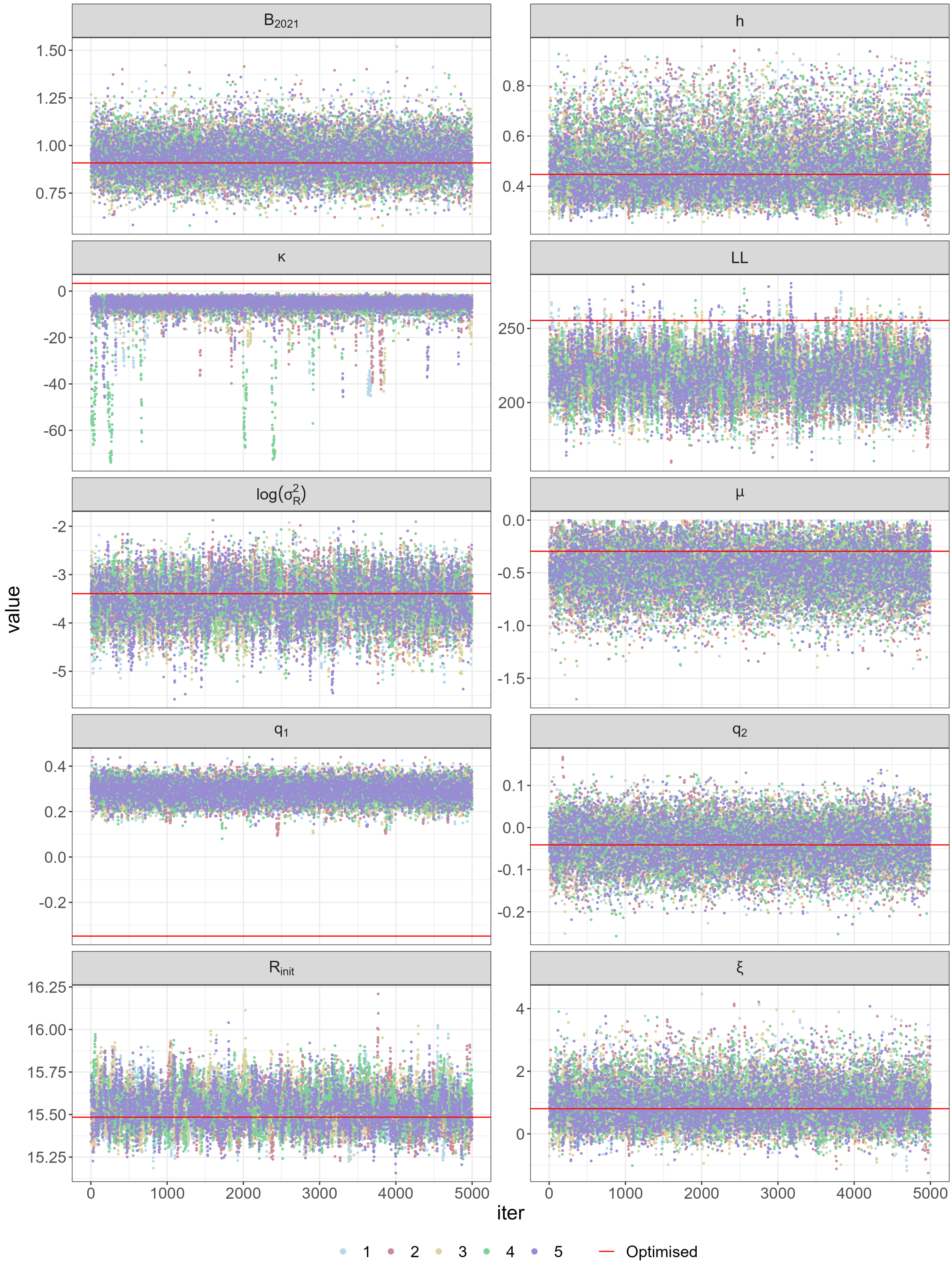


Figure B.46: Trace plot of MCMC chains for mud bugs scenario 7. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

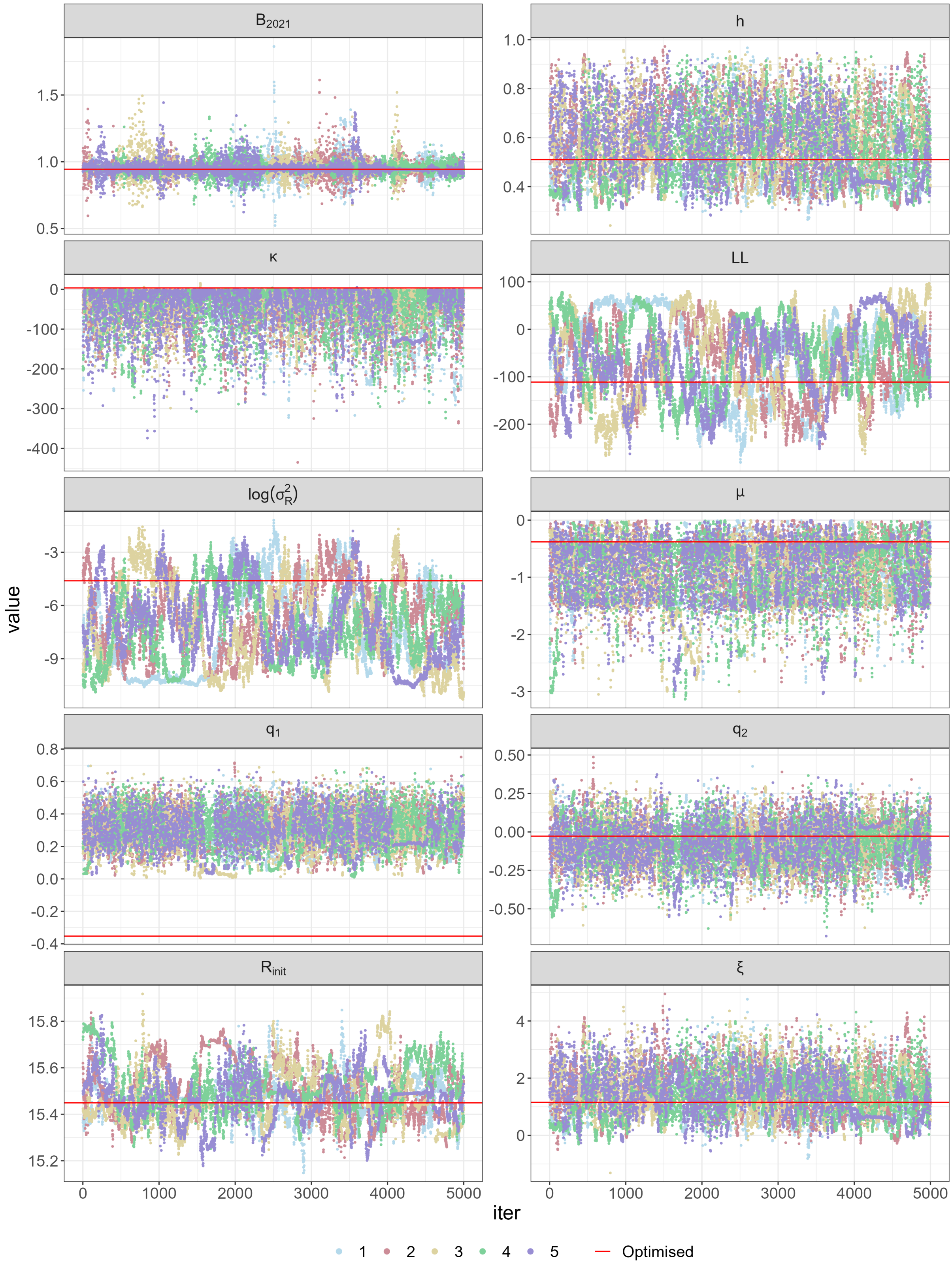


Figure B.47: Trace plot of MCMC chains for mud bugs scenario 8. ‘Optimised’ shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

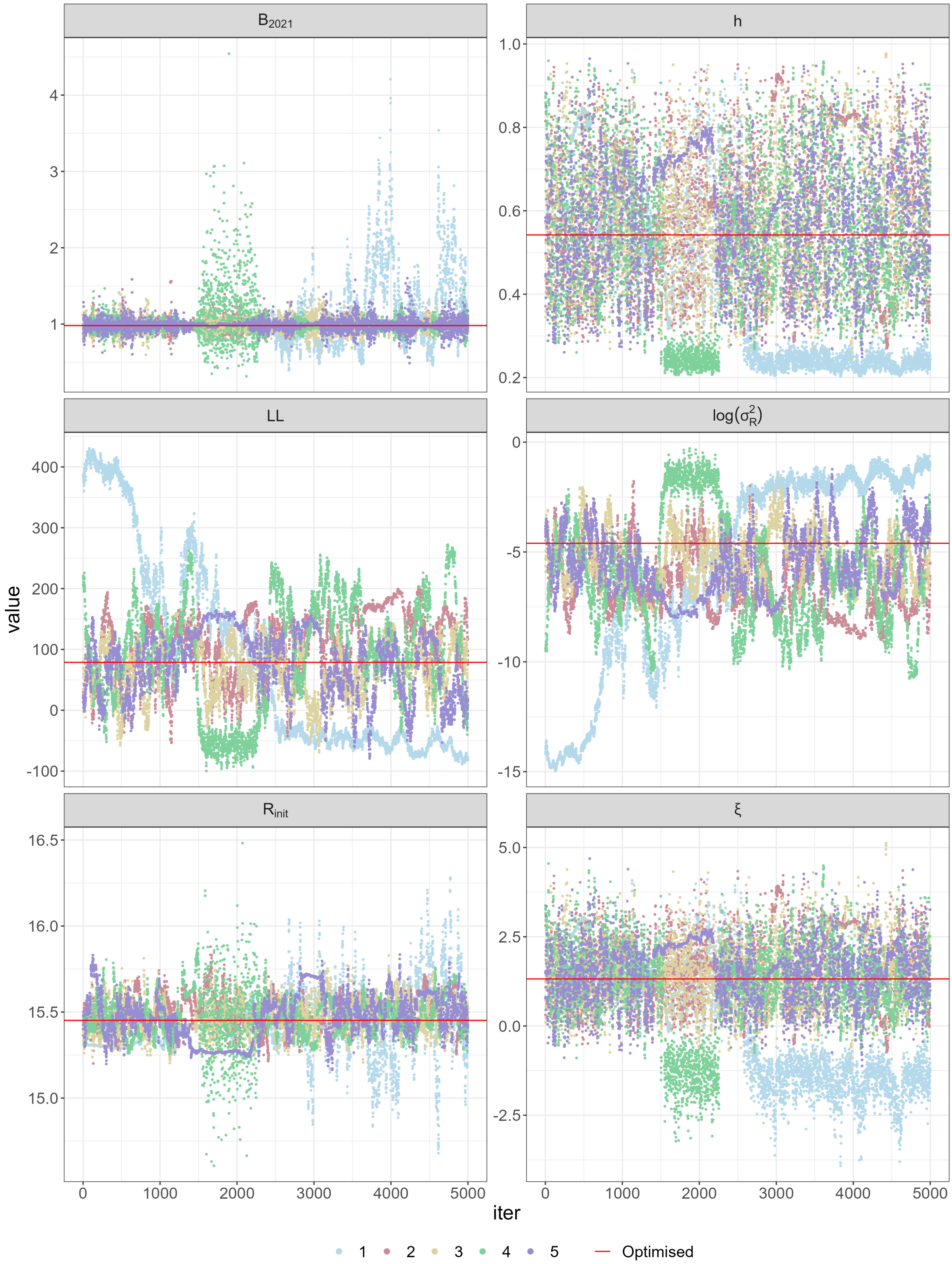


Figure B.48: Trace plot of MCMC chains for mud bugs scenario 9. ‘Optimised’ shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

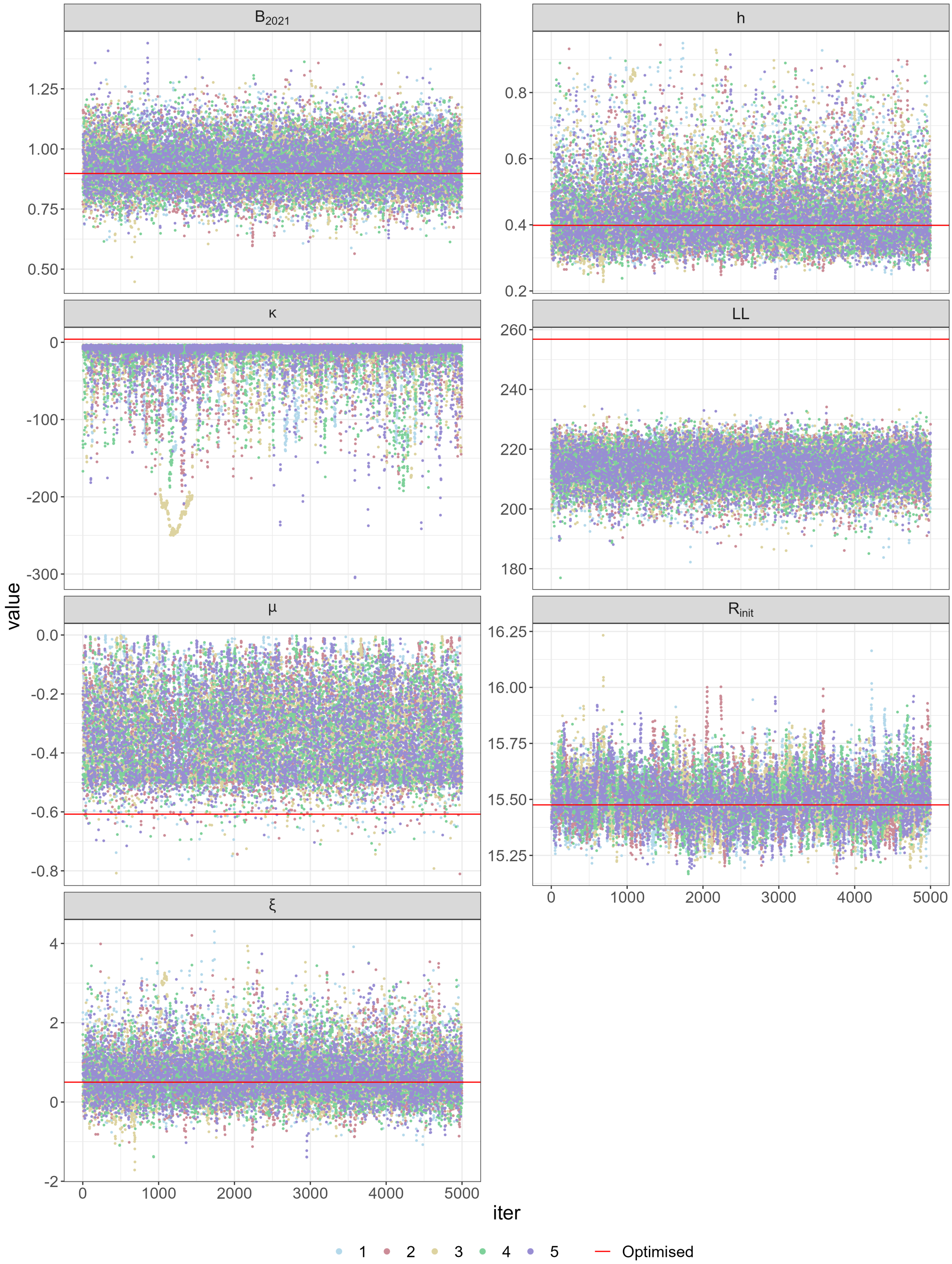


Figure B.49: Trace plot of MCMC chains for mud bugs scenario 10. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

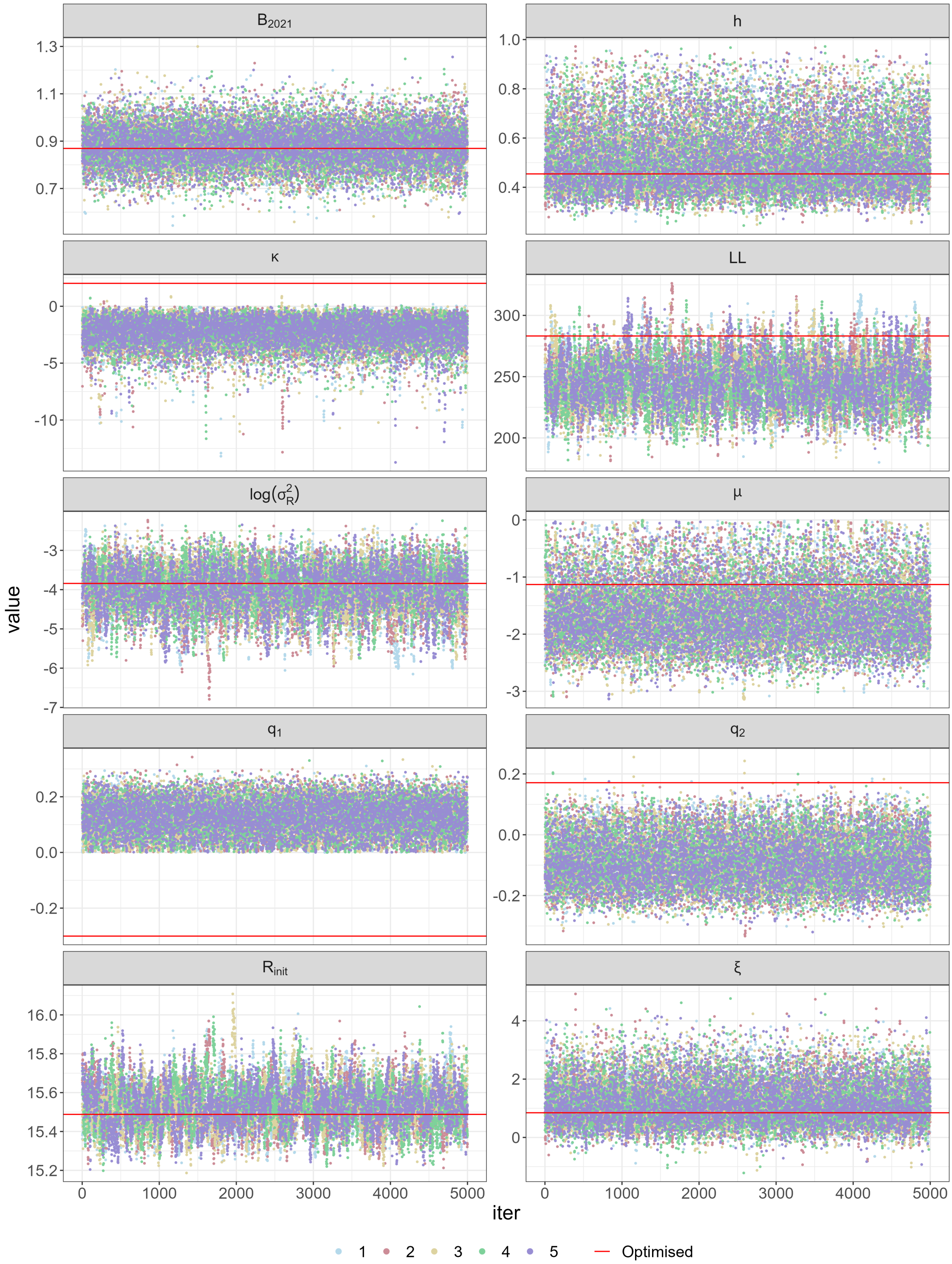


Figure B.50: Trace plot of MCMC chains for mud bugs scenario 11. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

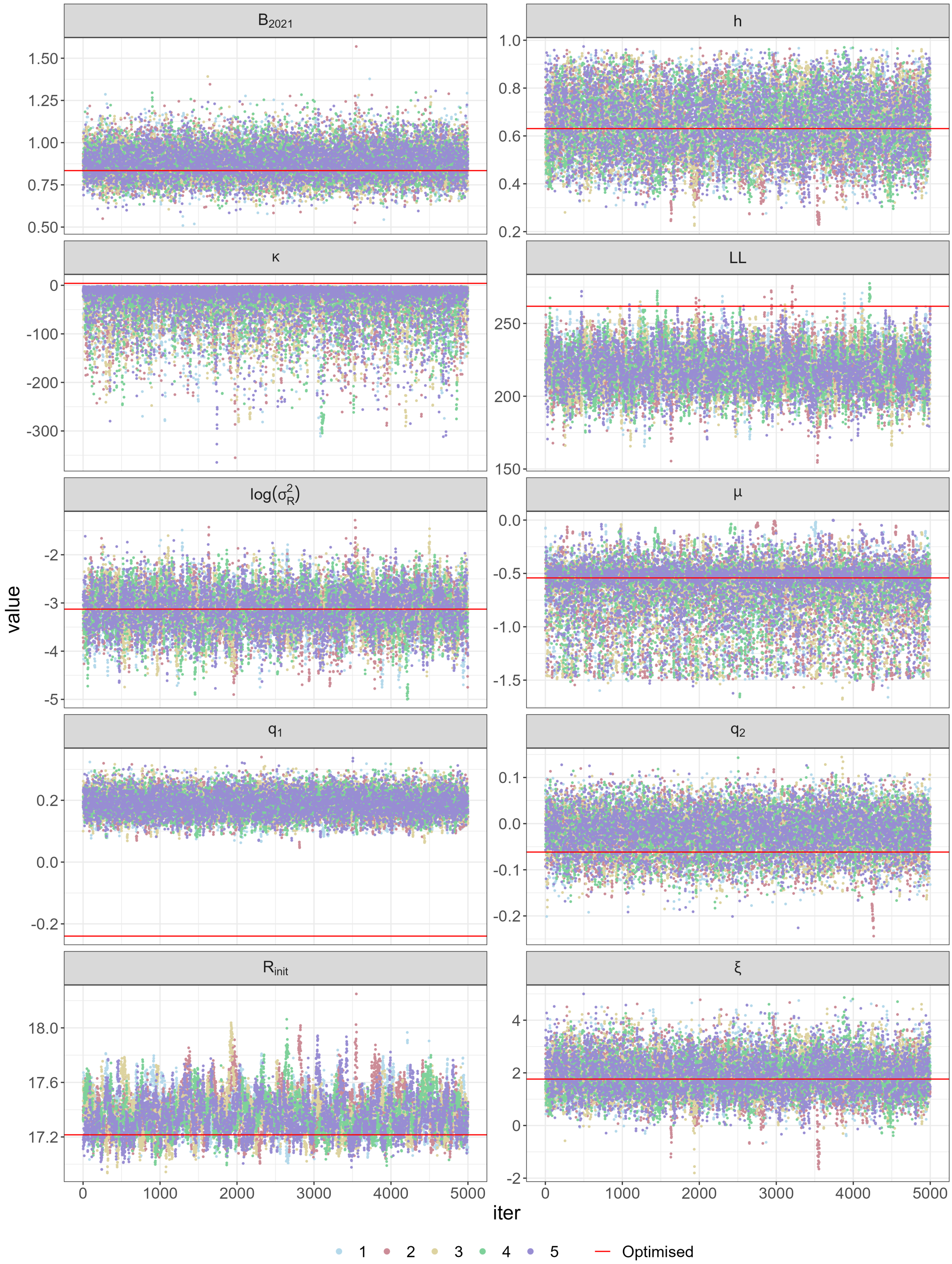


Figure B.51: Trace plot of MCMC chains for mud bugs scenario 12. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. There is a high probability that this scenario has converged

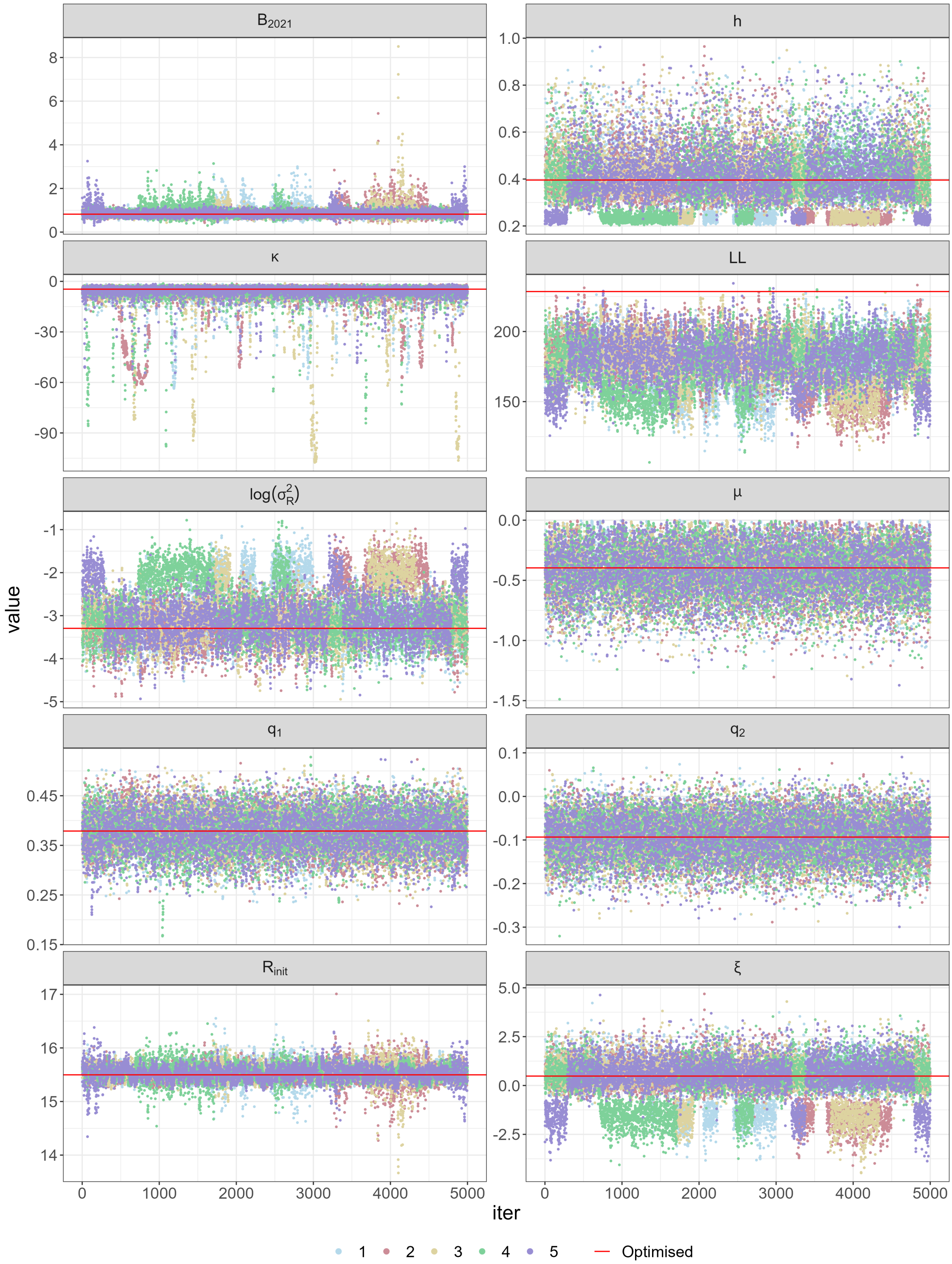


Figure B.52: Trace plot of MCMC chains for mud bugs scenario 13. 'Optimised' shows the parameter value found from maximum likelihood estimate results using the *optim* function. This scenario has not converged

B.1.3 Correlation

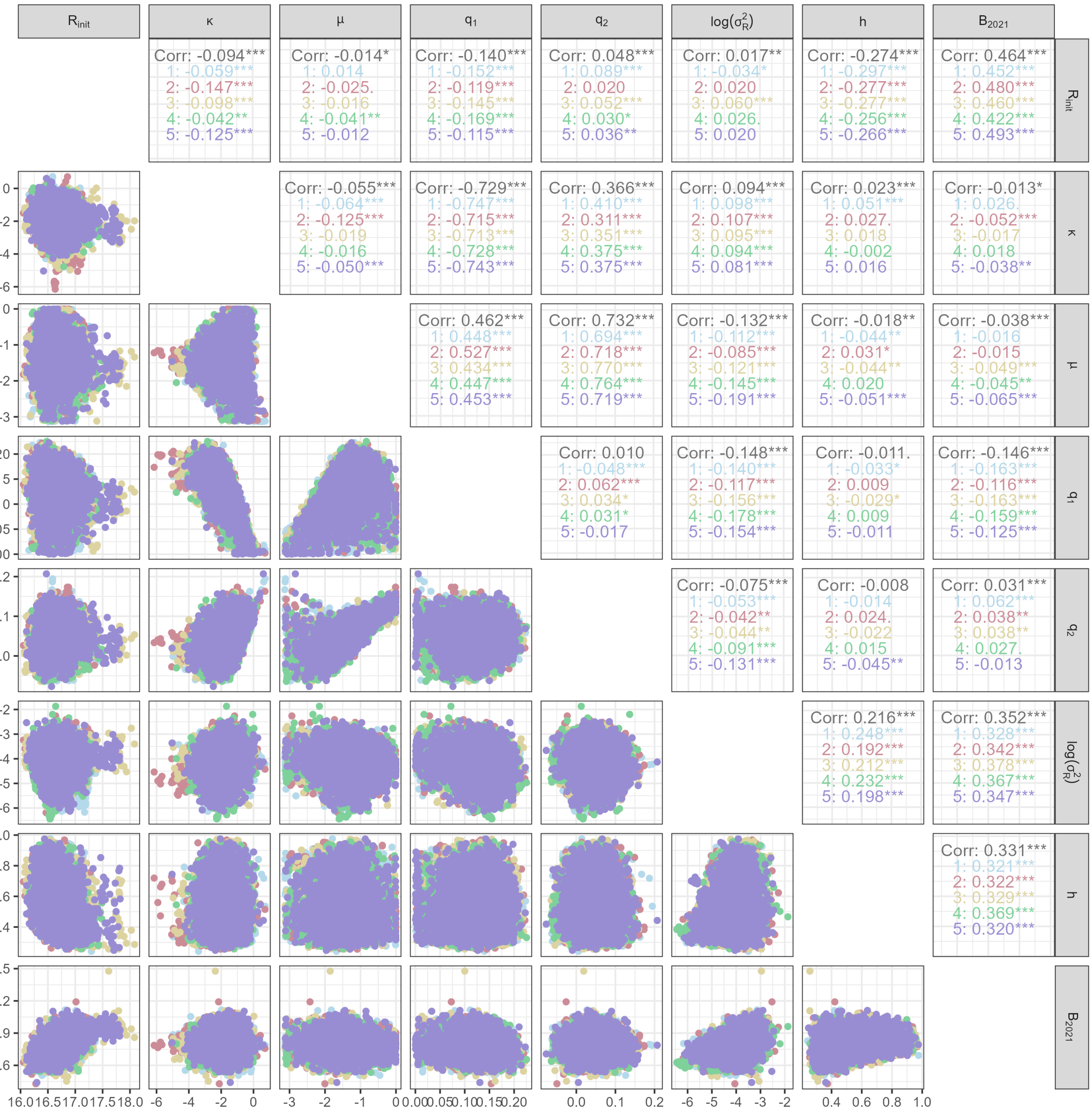


Figure B.53: Correlation plot of MCMC chains for sand bugs scenario 1. Colours distinguish chain and associated correlation.

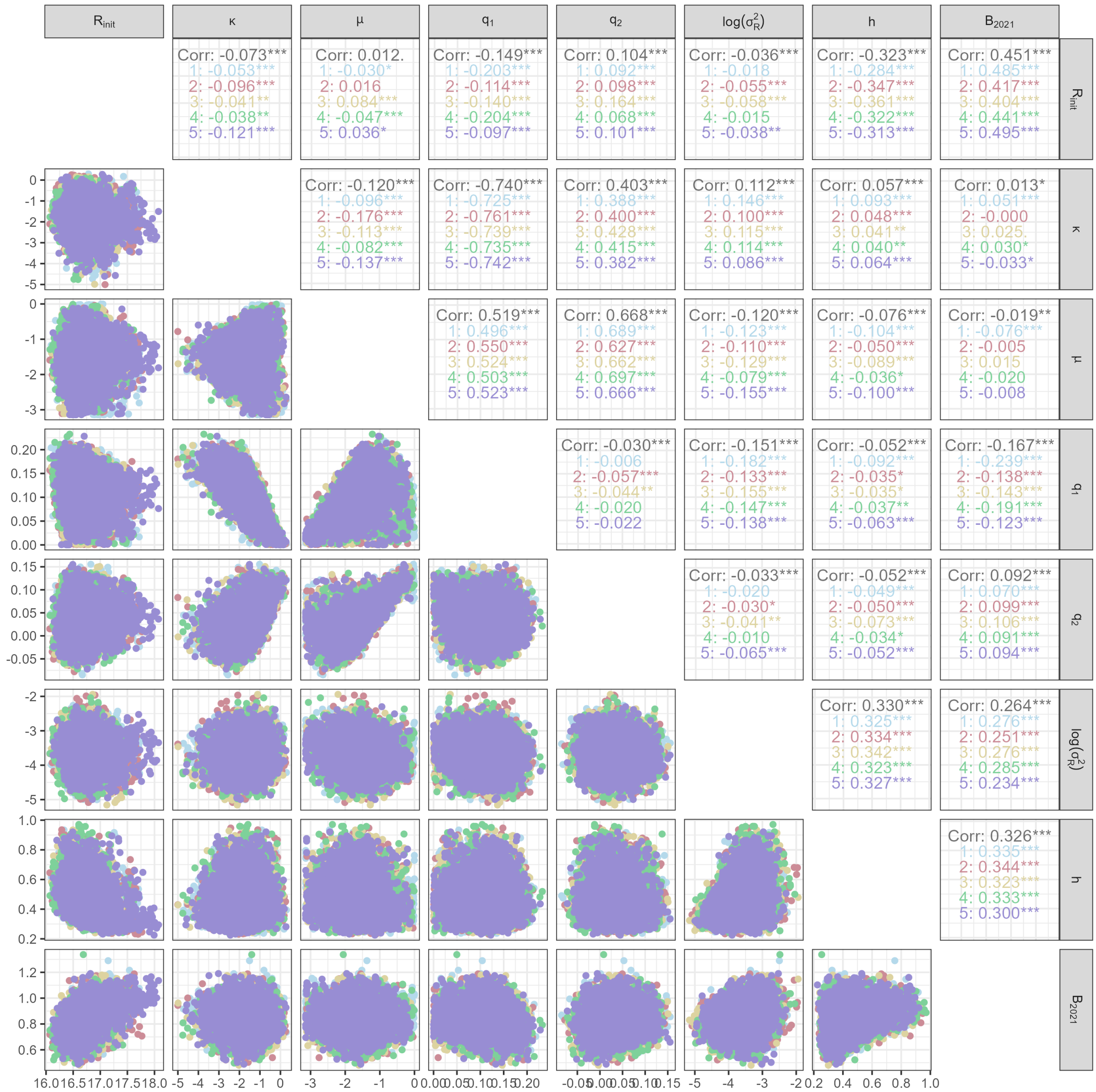


Figure B.54: Correlation plot of MCMC chains for sand bugs scenario 2. Colours distinguish chain and associated correlation.

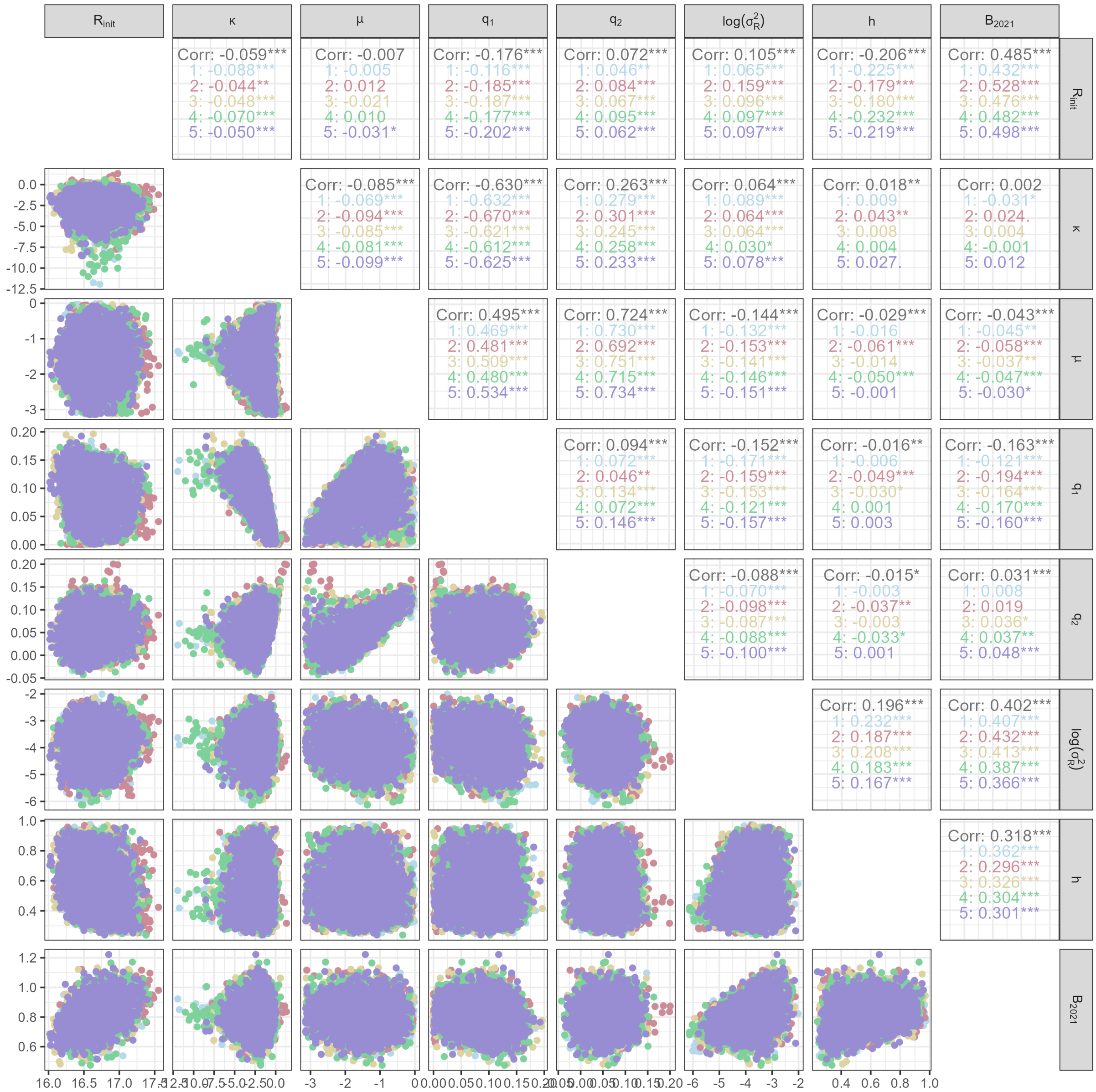


Figure B.55: Correlation plot of MCMC chains for sand bugs scenario 3. Colours distinguish chain and associated correlation.

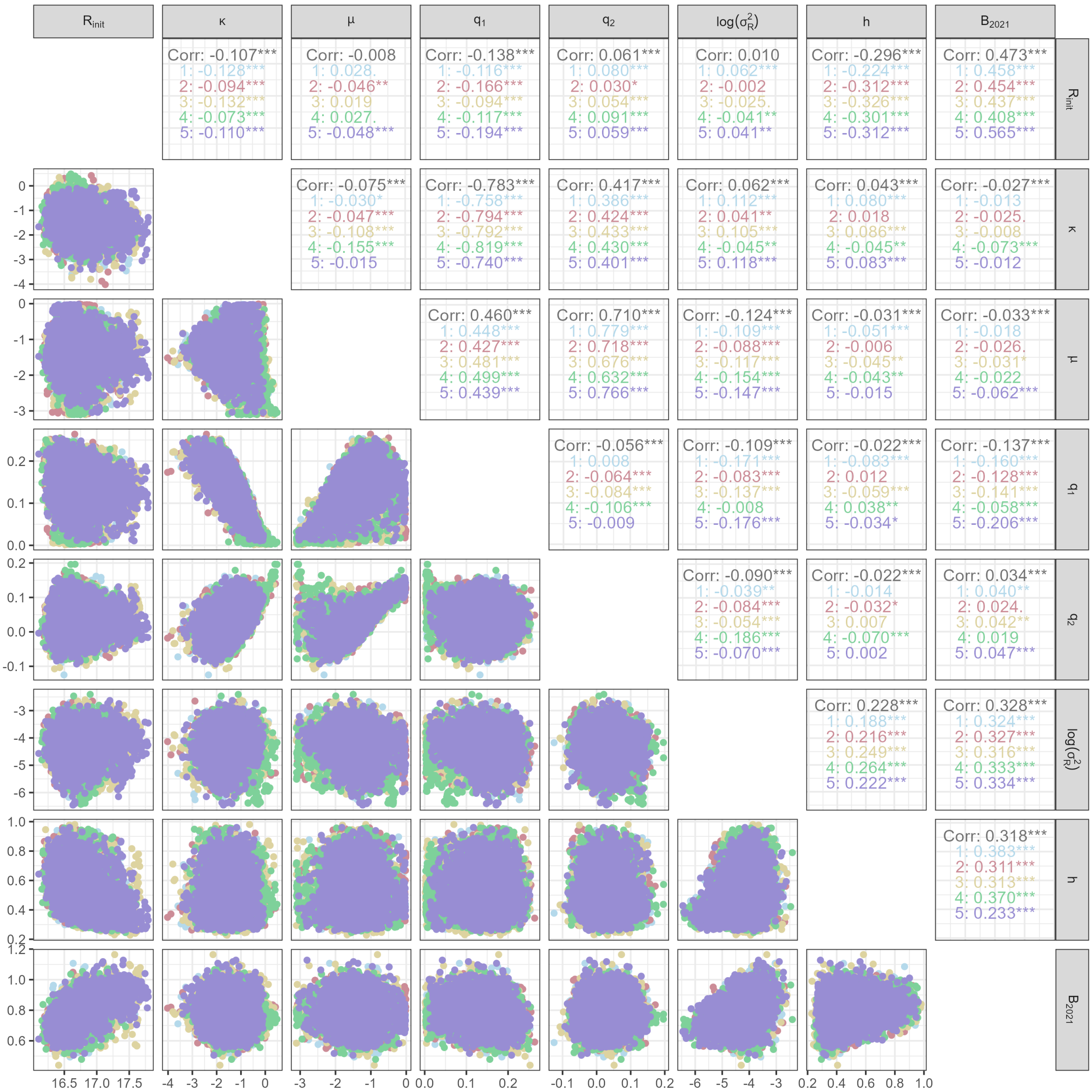


Figure B.56: Correlation plot of MCMC chains for sand bugs scenario 4. Colours distinguish chain and associated correlation.

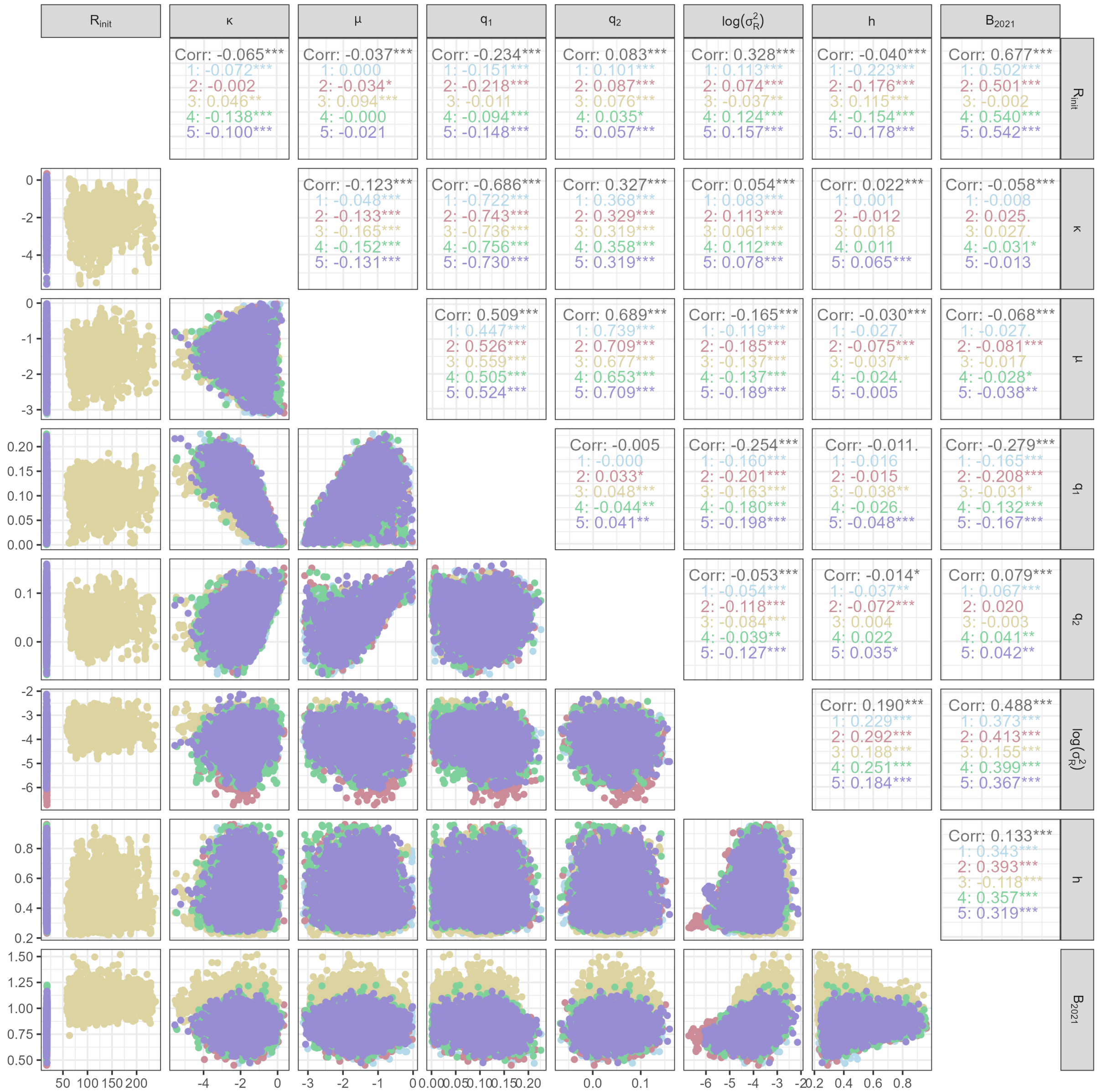


Figure B.57: Correlation plot of MCMC chains for sand bugs scenario 5. Colours distinguish chain and associated correlation.

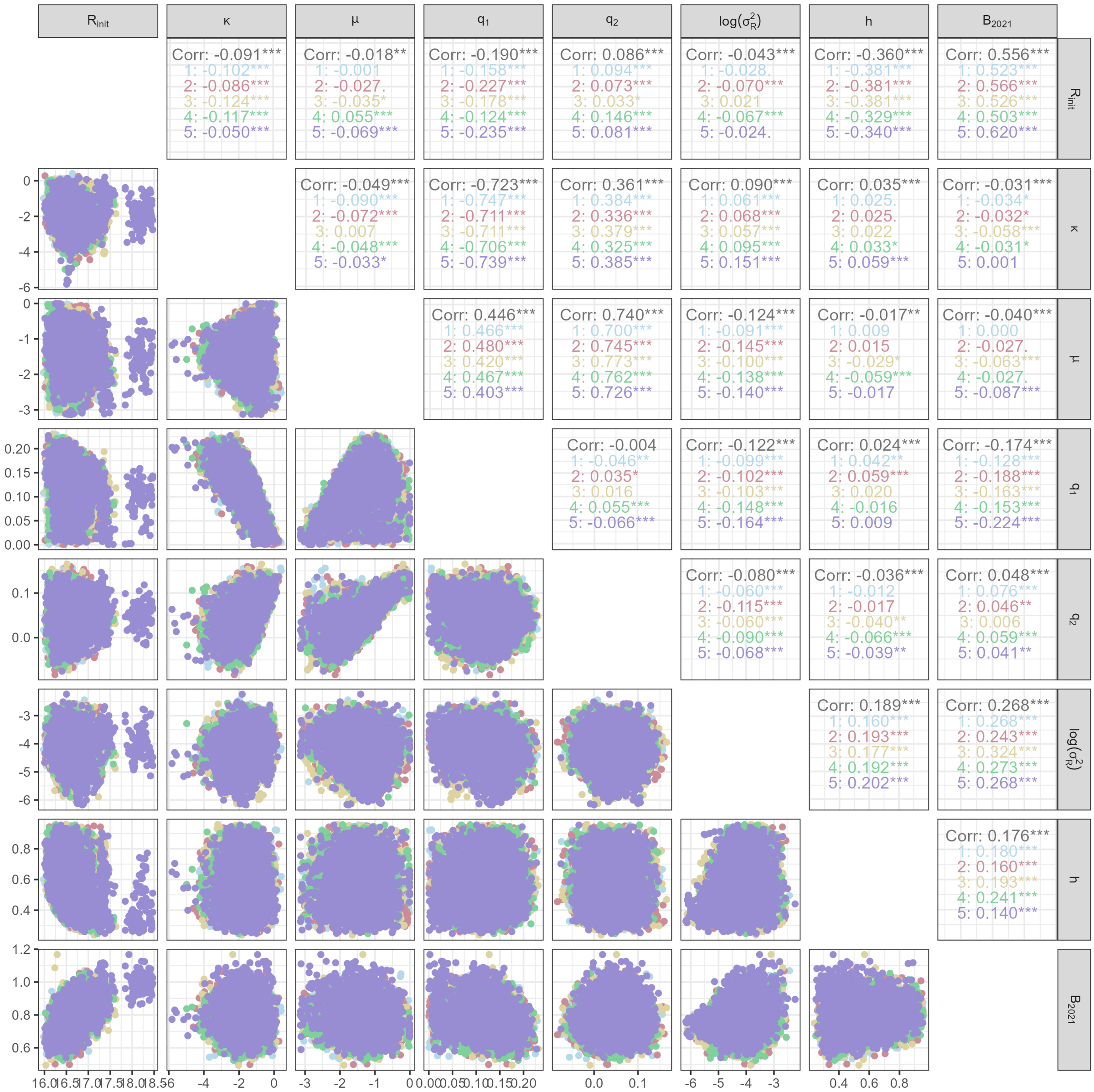


Figure B.58: Correlation plot of MCMC chains for sand bugs scenario 6. Colours distinguish chain and associated correlation.

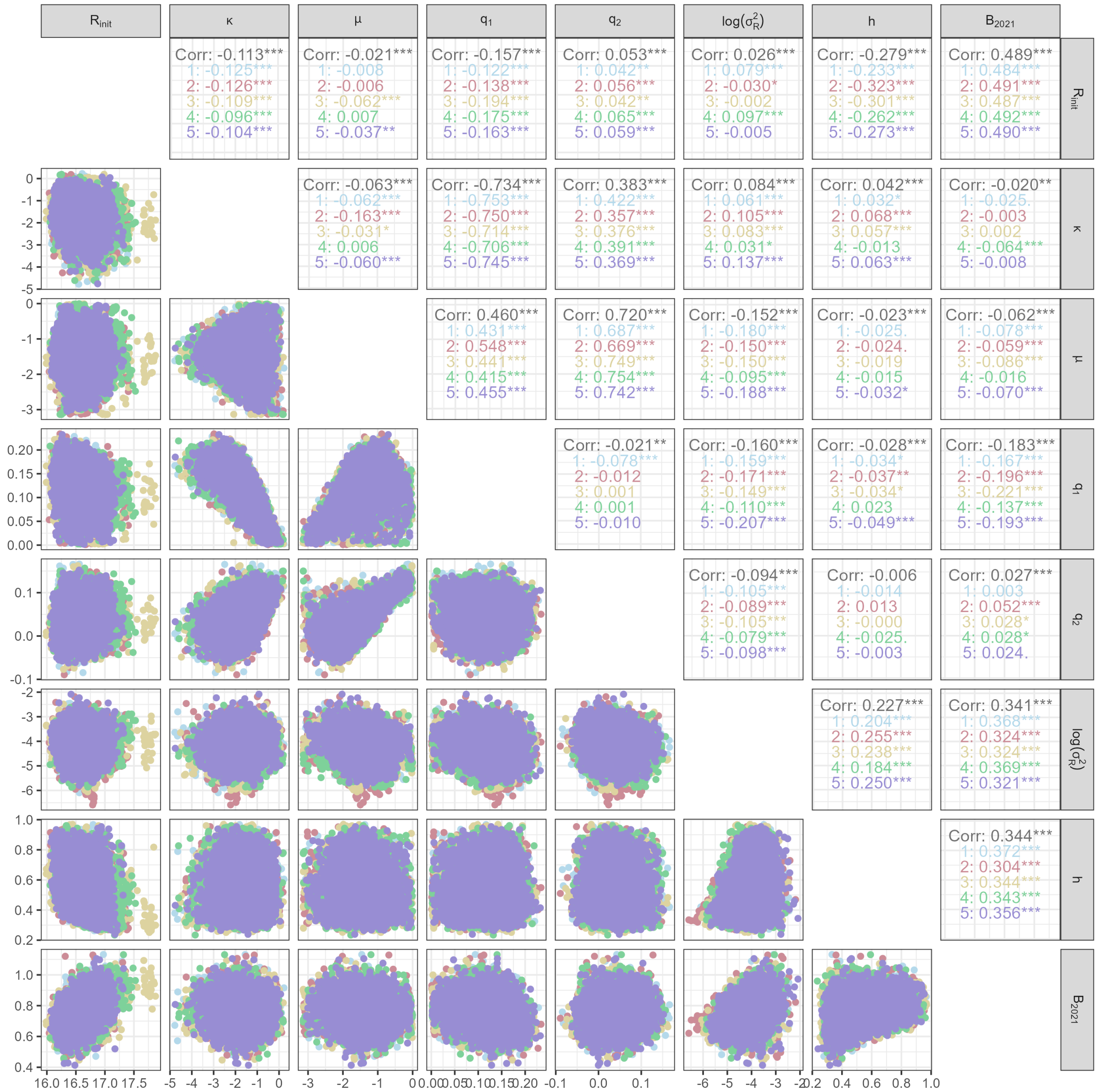


Figure B.59: Correlation plot of MCMC chains for sand bugs scenario 7. Colours distinguish chain and associated correlation.

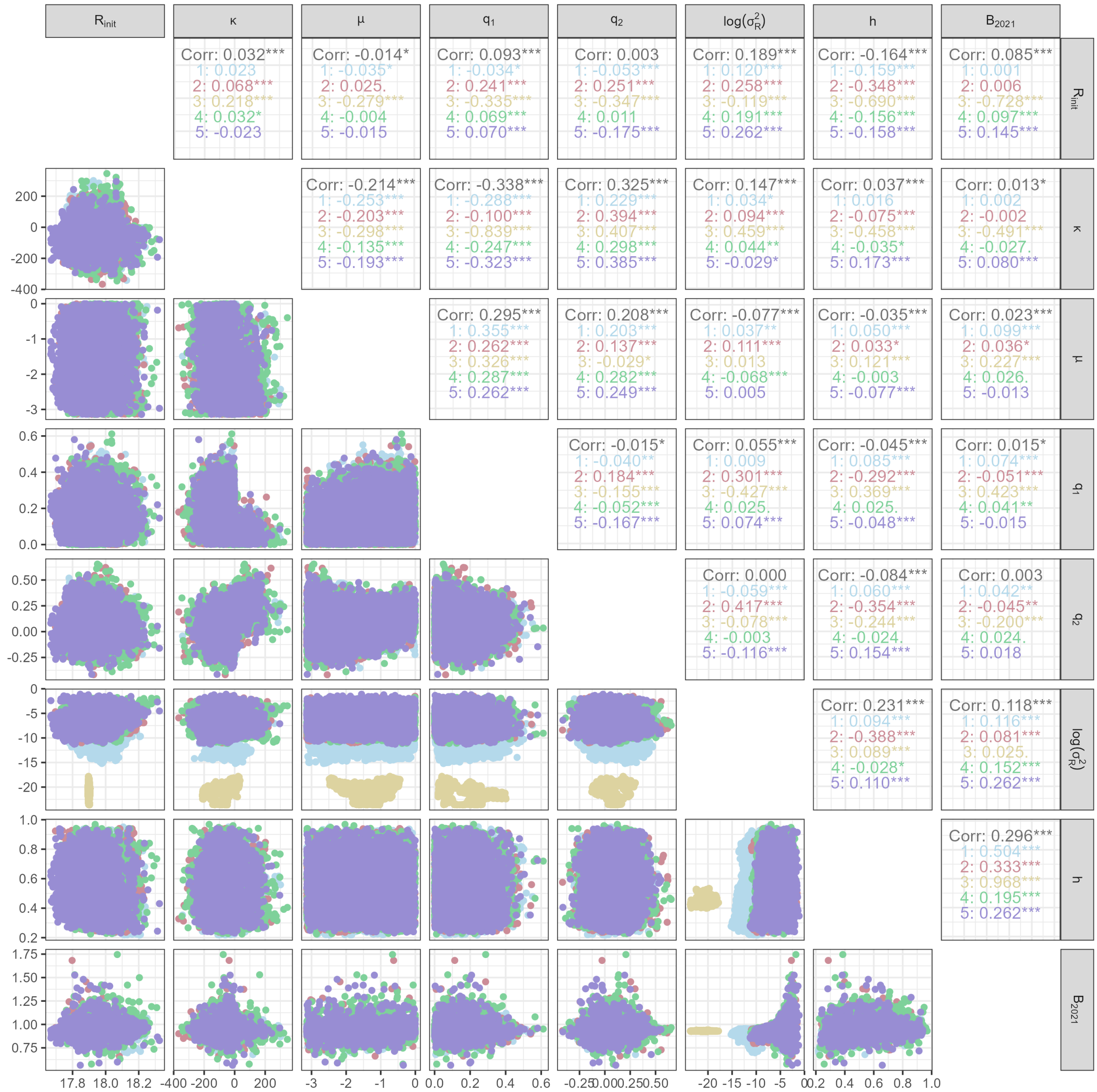


Figure B.60: Correlation plot of MCMC chains for sand bugs scenario 8. Colours distinguish chain and associated correlation.

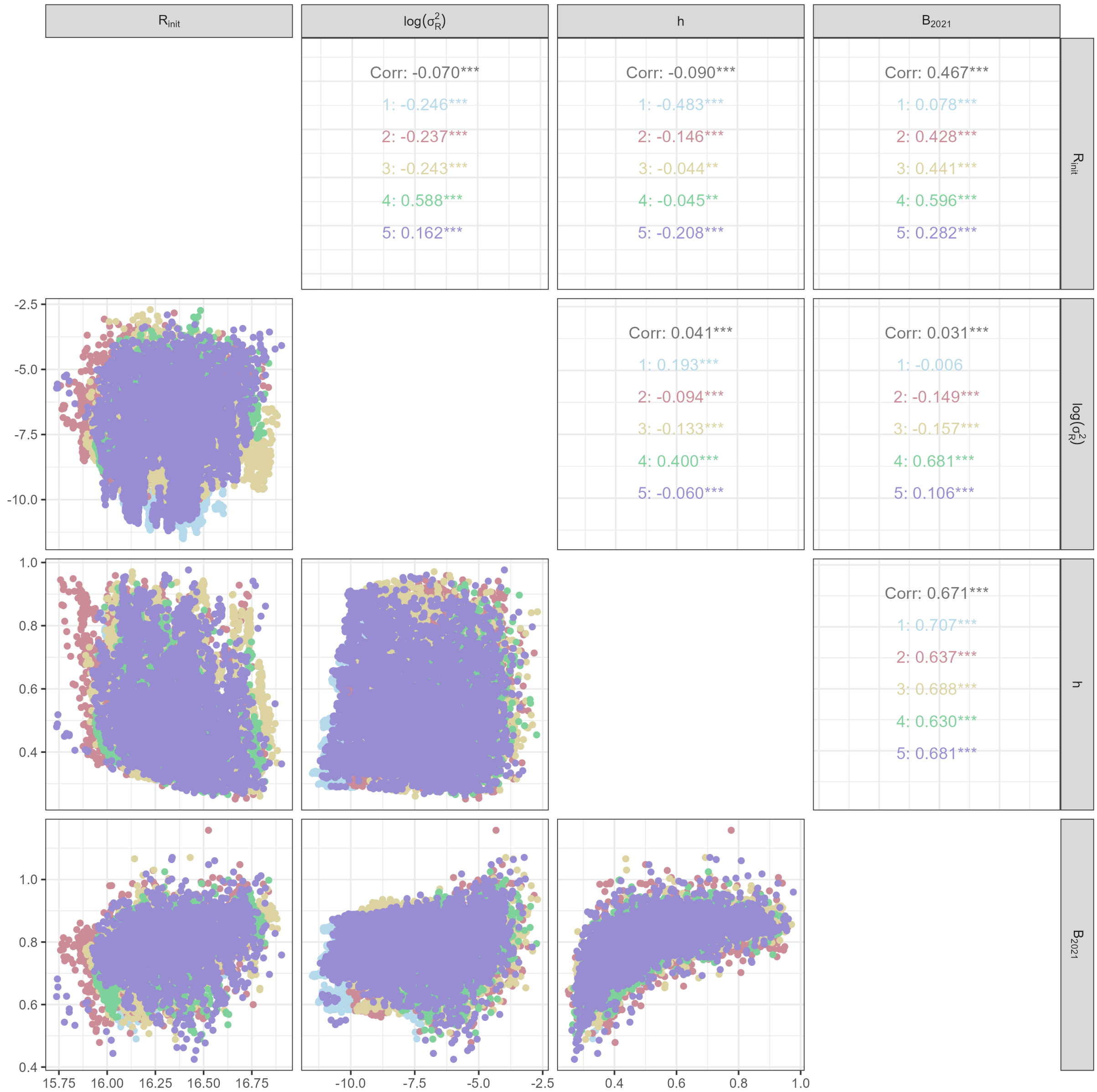


Figure B.61: Correlation plot of MCMC chains for sand bugs scenario 9. Colours distinguish chain and associated correlation.

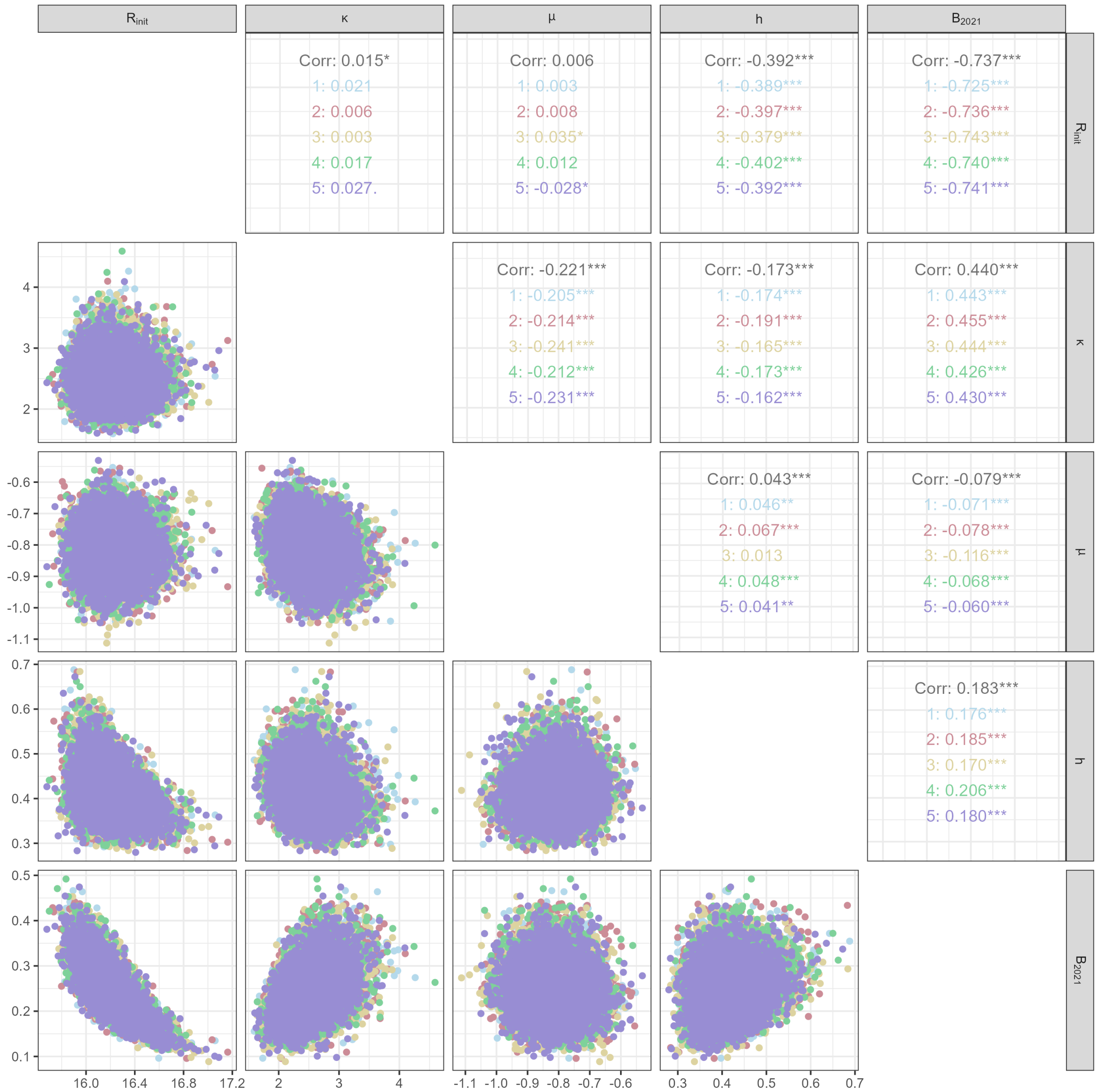


Figure B.62: Correlation plot of MCMC chains for sand bugs scenario 10. Colours distinguish chain and associated correlation.

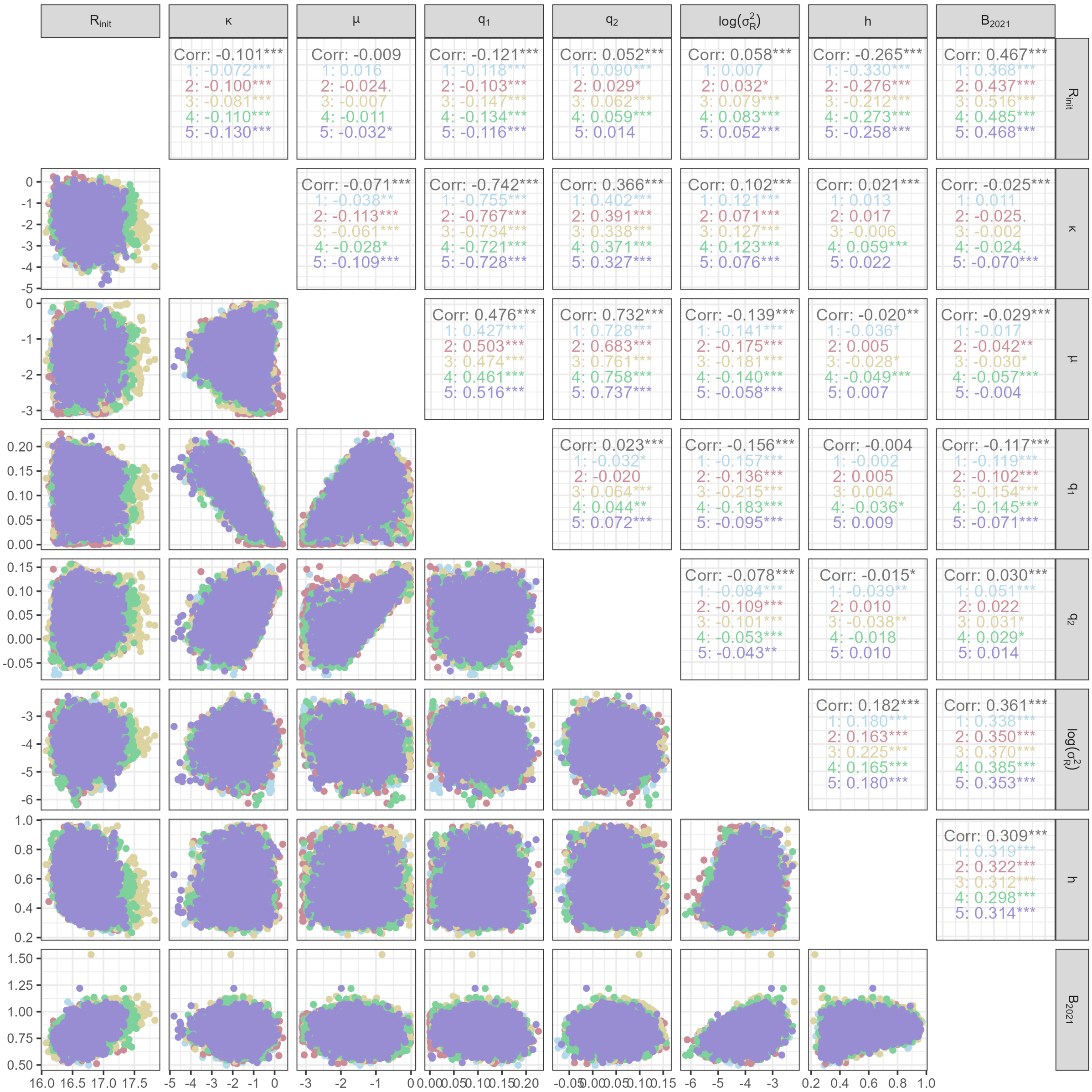


Figure B.63: Correlation plot of MCMC chains for sand bugs scenario 11. Colours distinguish chain and associated correlation.

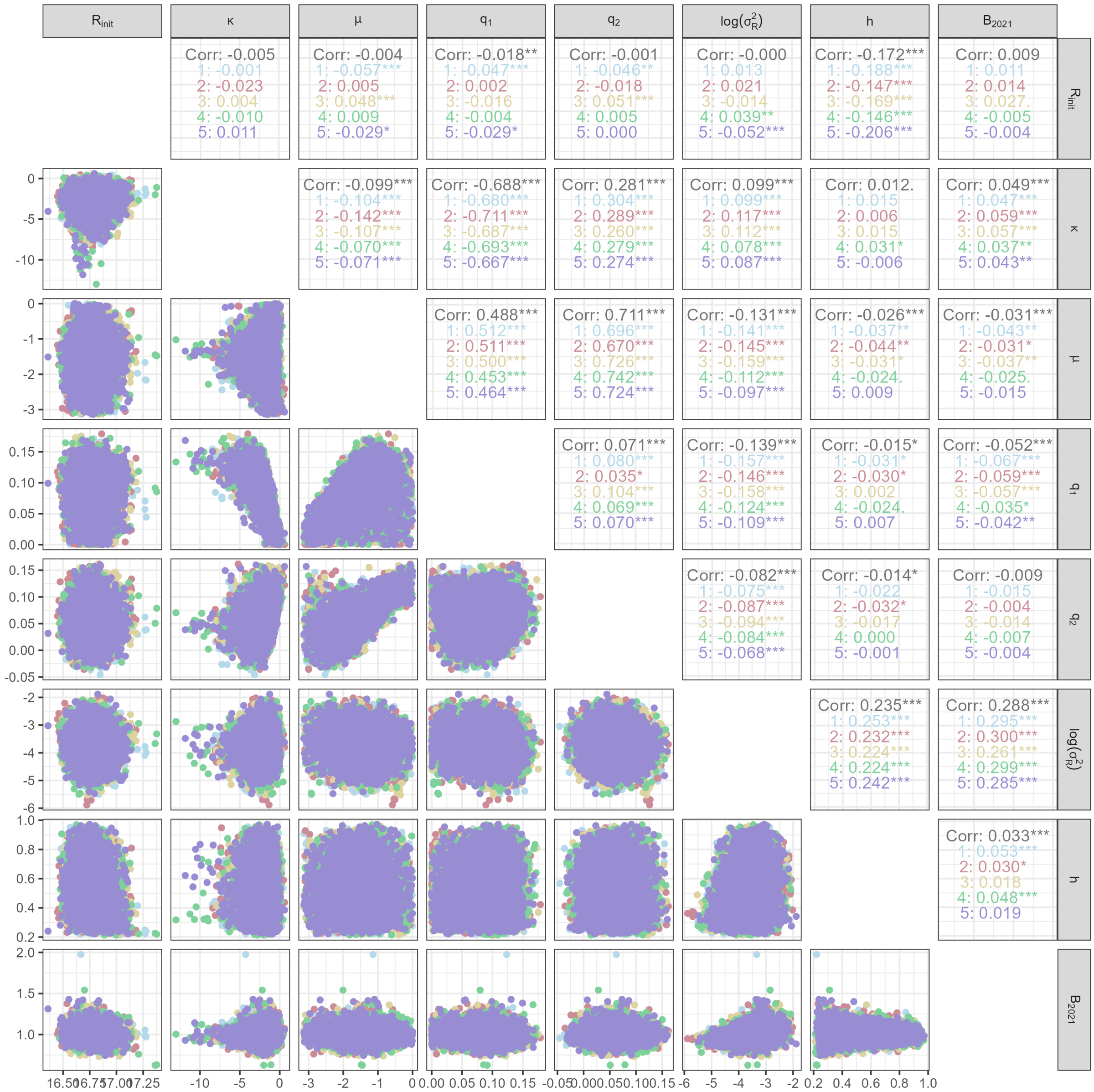


Figure B.64: Correlation plot of MCMC chains for sand bugs scenario 12. Colours distinguish chain and associated correlation.

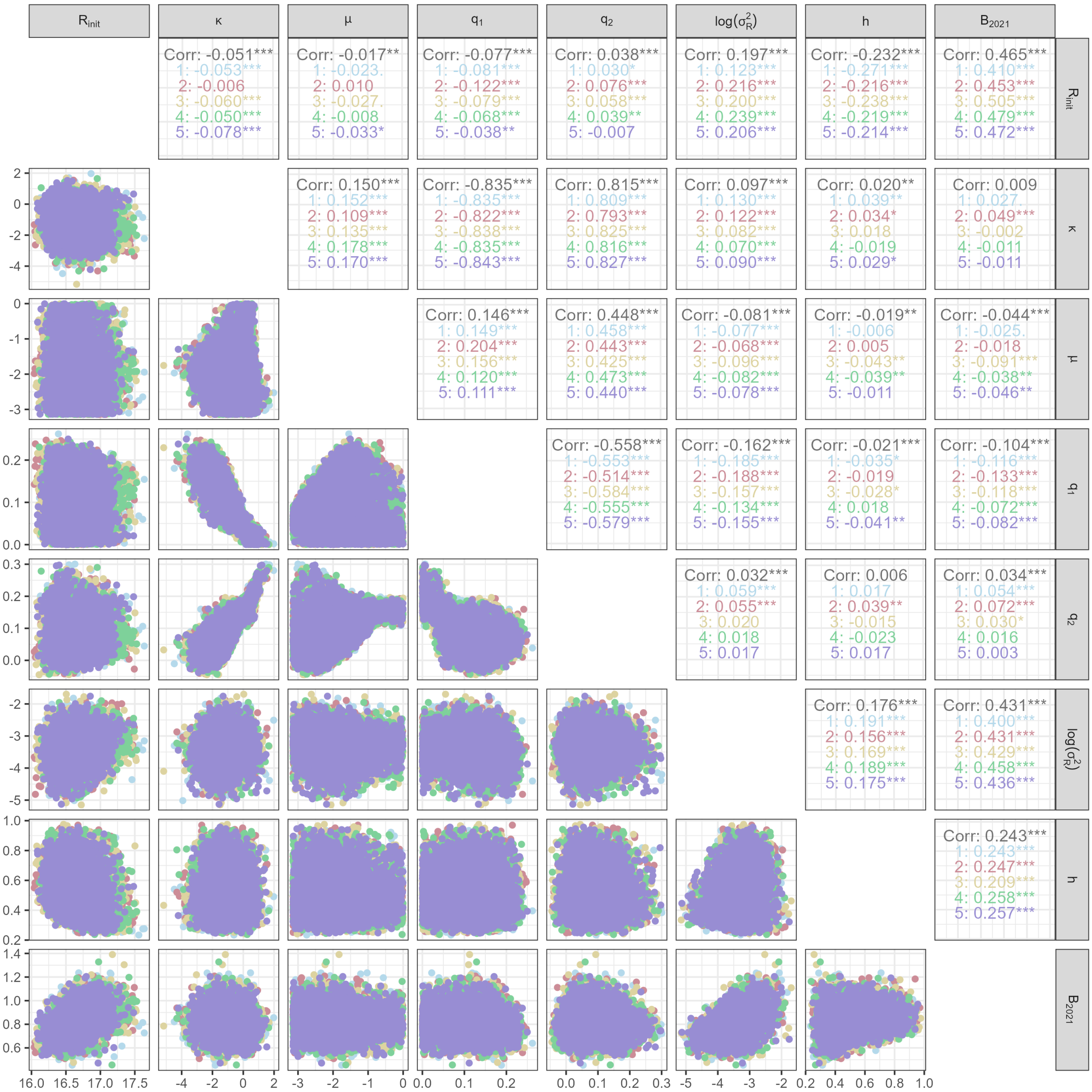


Figure B.65: Correlation plot of MCMC chains for sand bugs scenario 13. Colours distinguish chain and associated correlation.

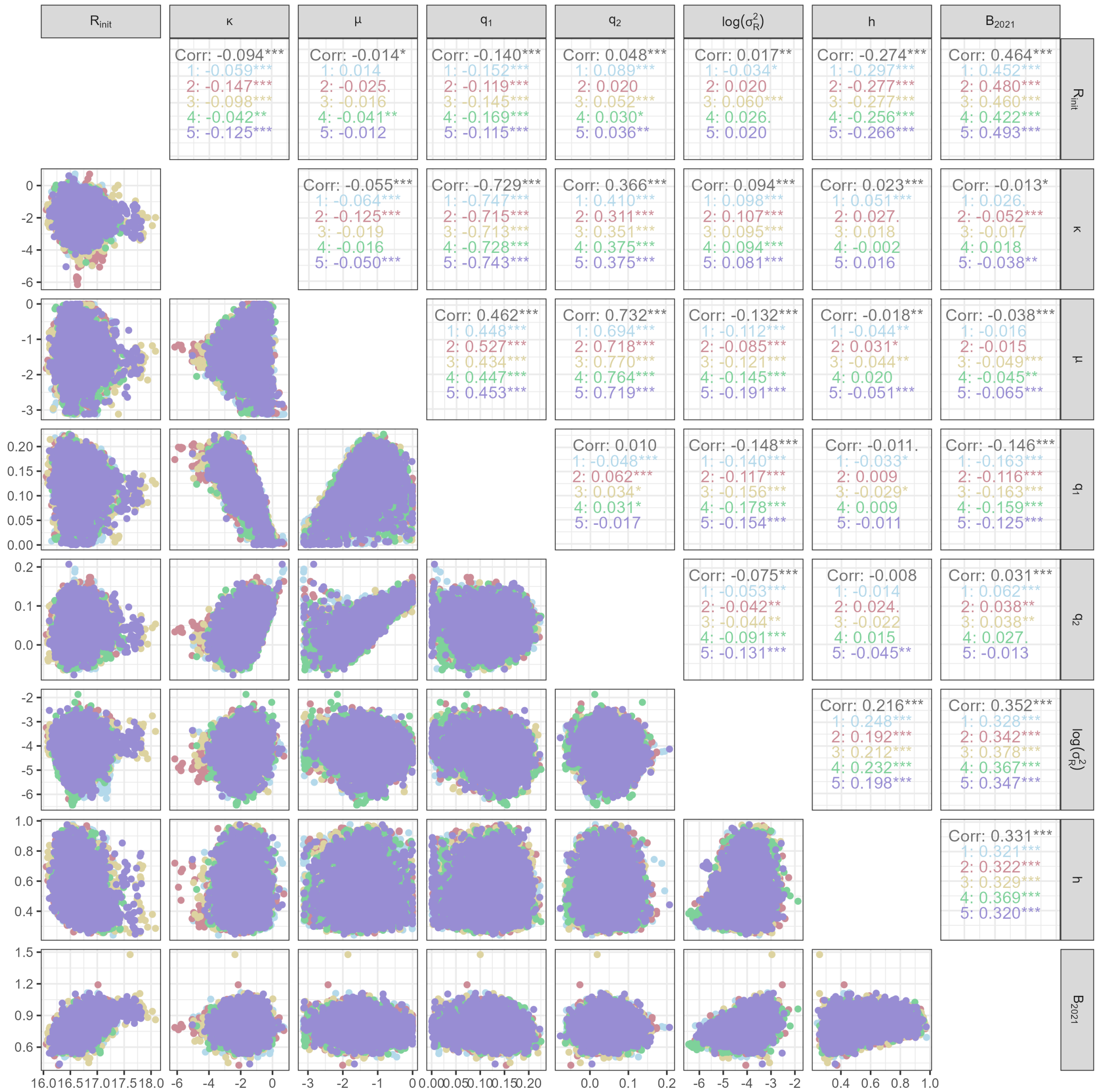


Figure B.66: Correlation plot of MCMC chains for mud bugs scenario 1. Colours distinguish chain and associated correlation.

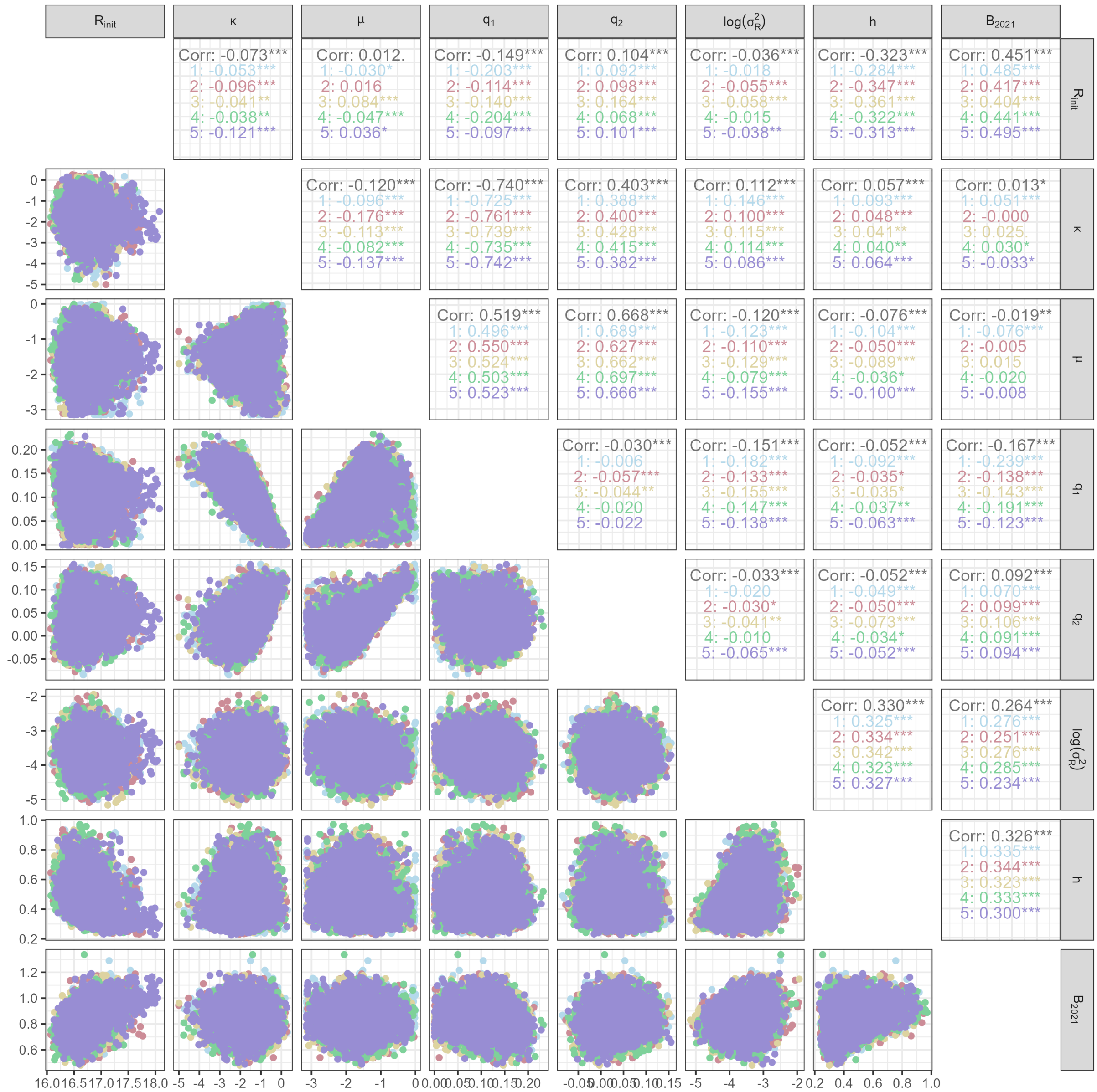


Figure B.67: Correlation plot of MCMC chains for mud bugs scenario 2. Colours distinguish chain and associated correlation.

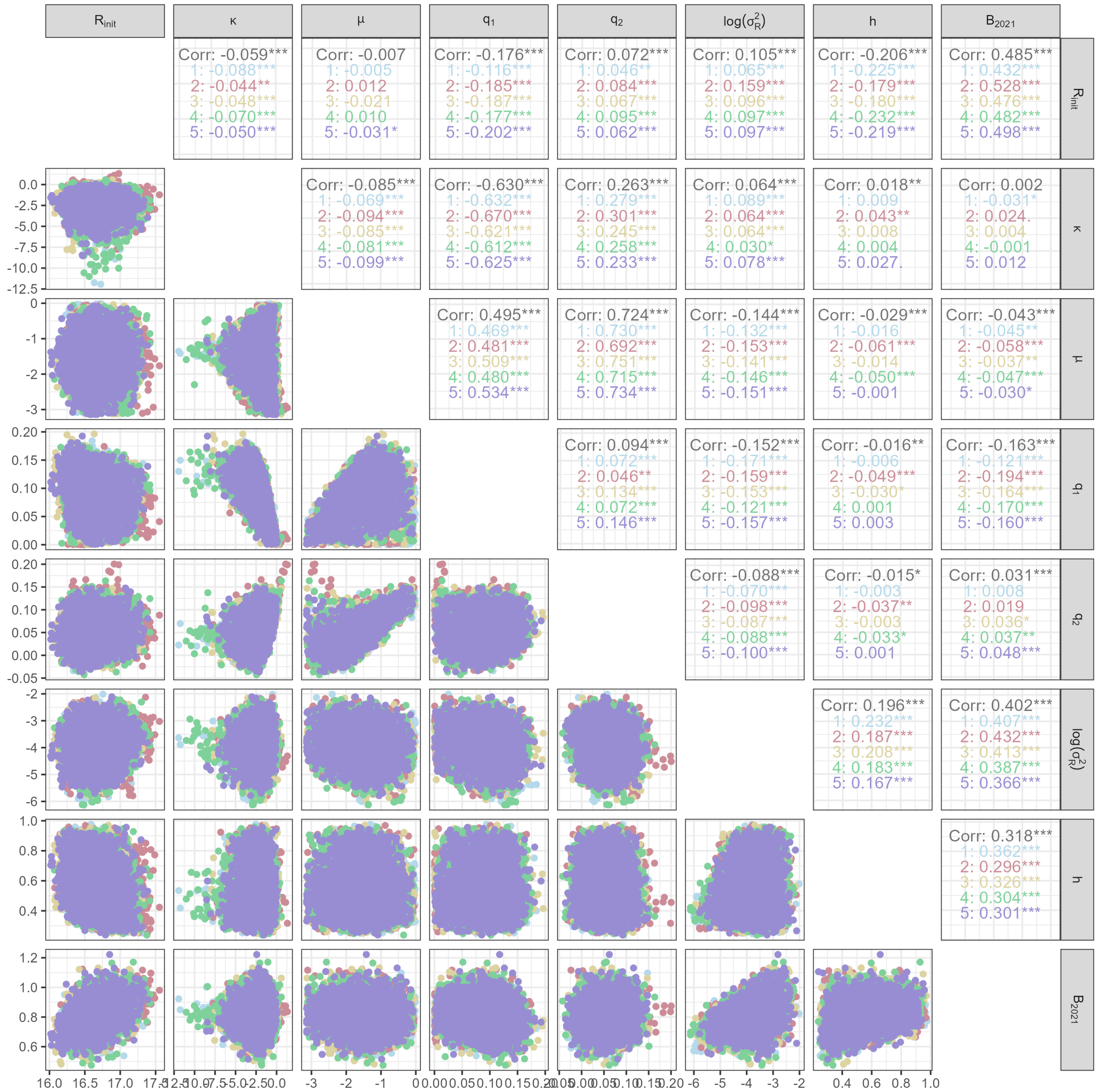


Figure B.68: Correlation plot of MCMC chains for mud bugs scenario 3. Colours distinguish chain and associated correlation.

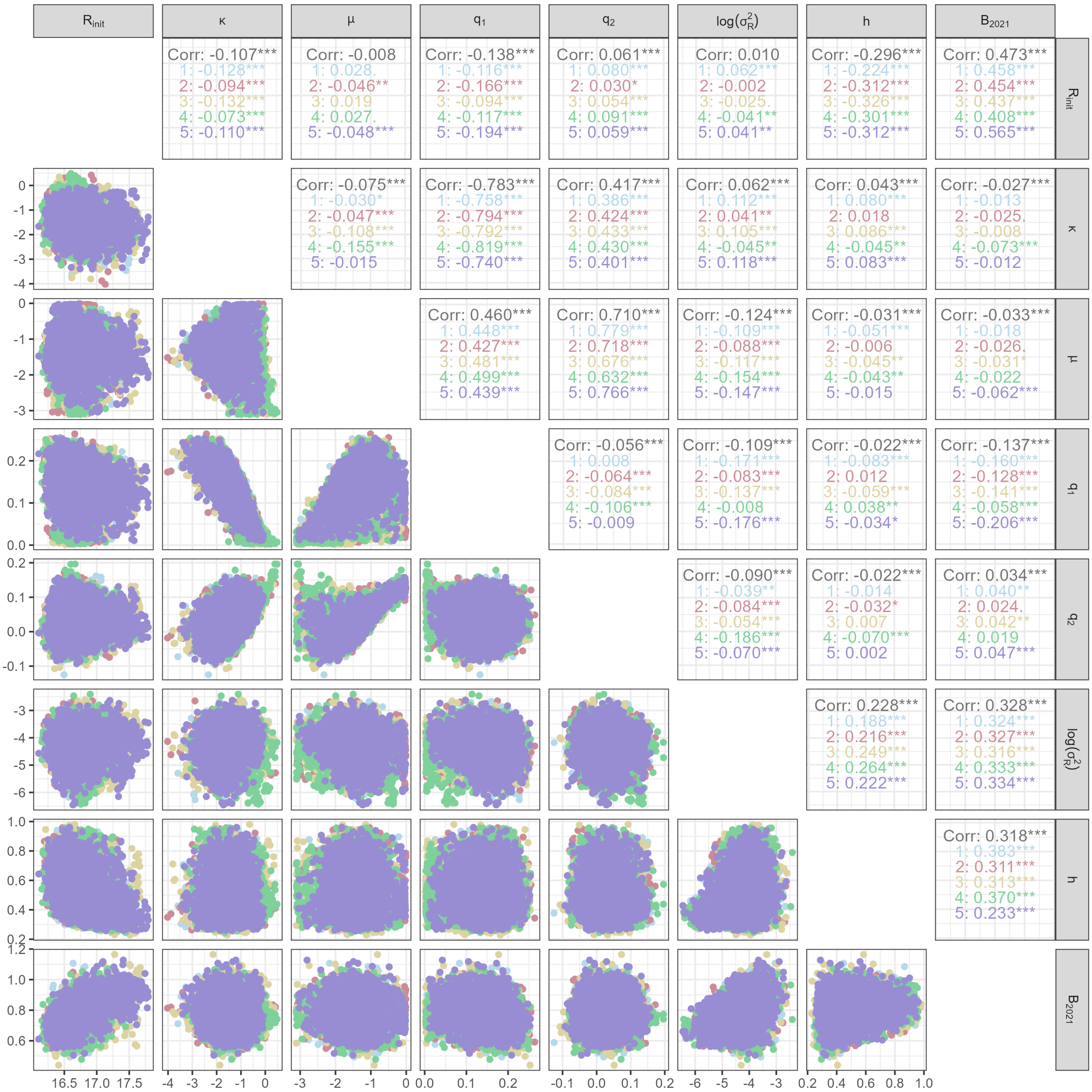


Figure B.69: Correlation plot of MCMC chains for mud bugs scenario 4. Colours distinguish chain and associated correlation.

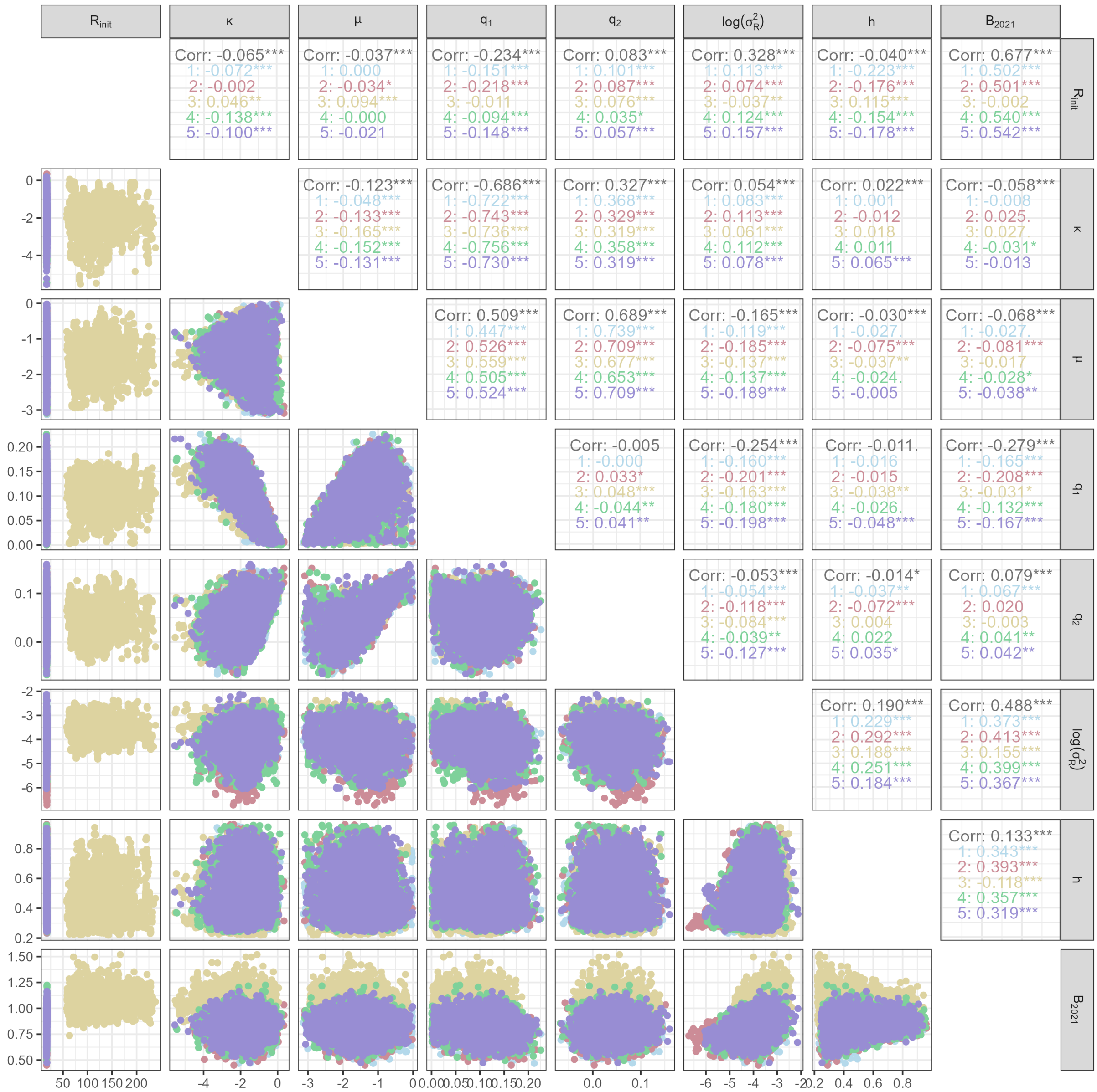


Figure B.70: Correlation plot of MCMC chains for mud bugs scenario 5. Colours distinguish chain and associated correlation.

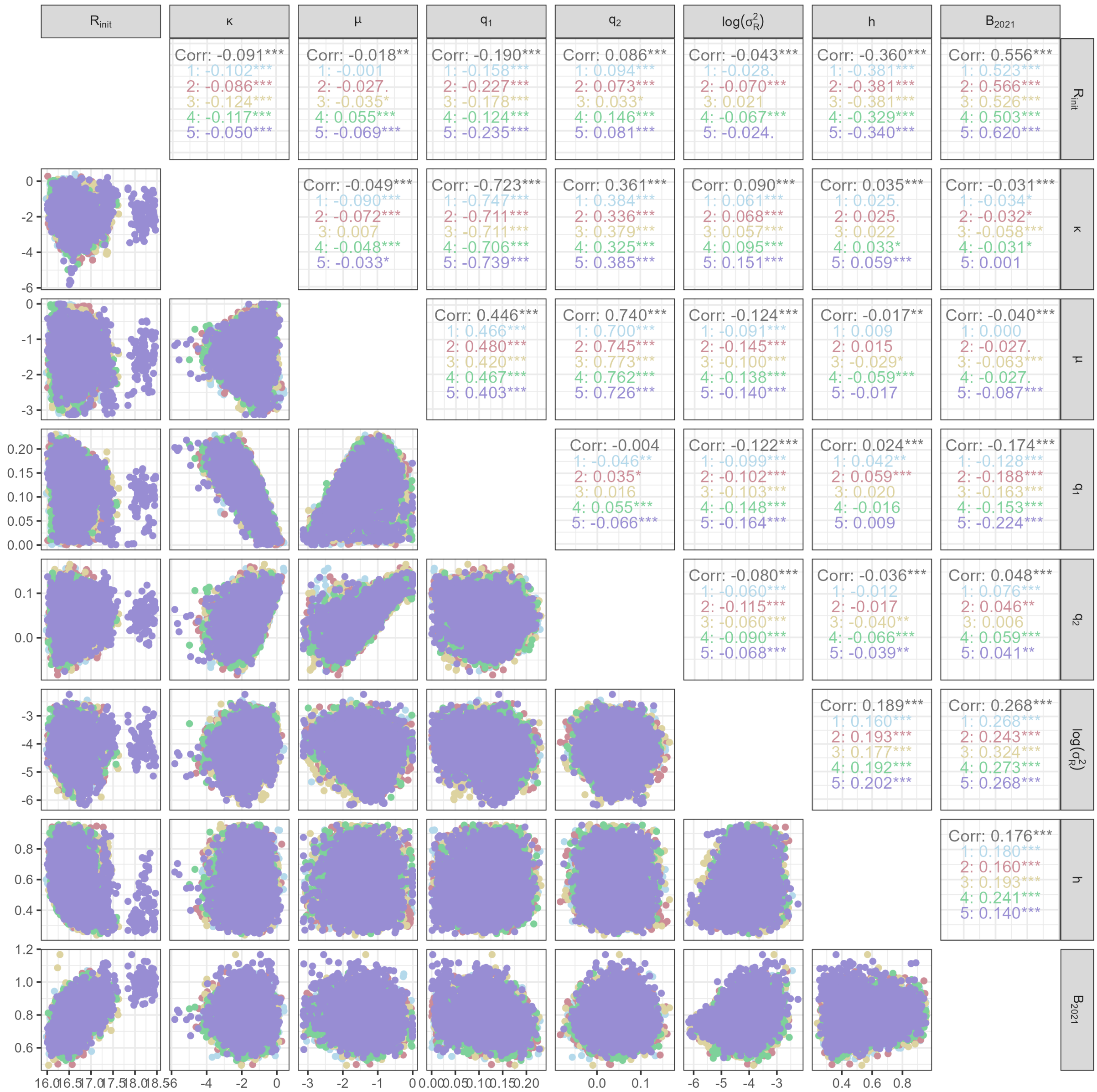


Figure B.71: Correlation plot of MCMC chains for mud bugs scenario 6. Colours distinguish chain and associated correlation.

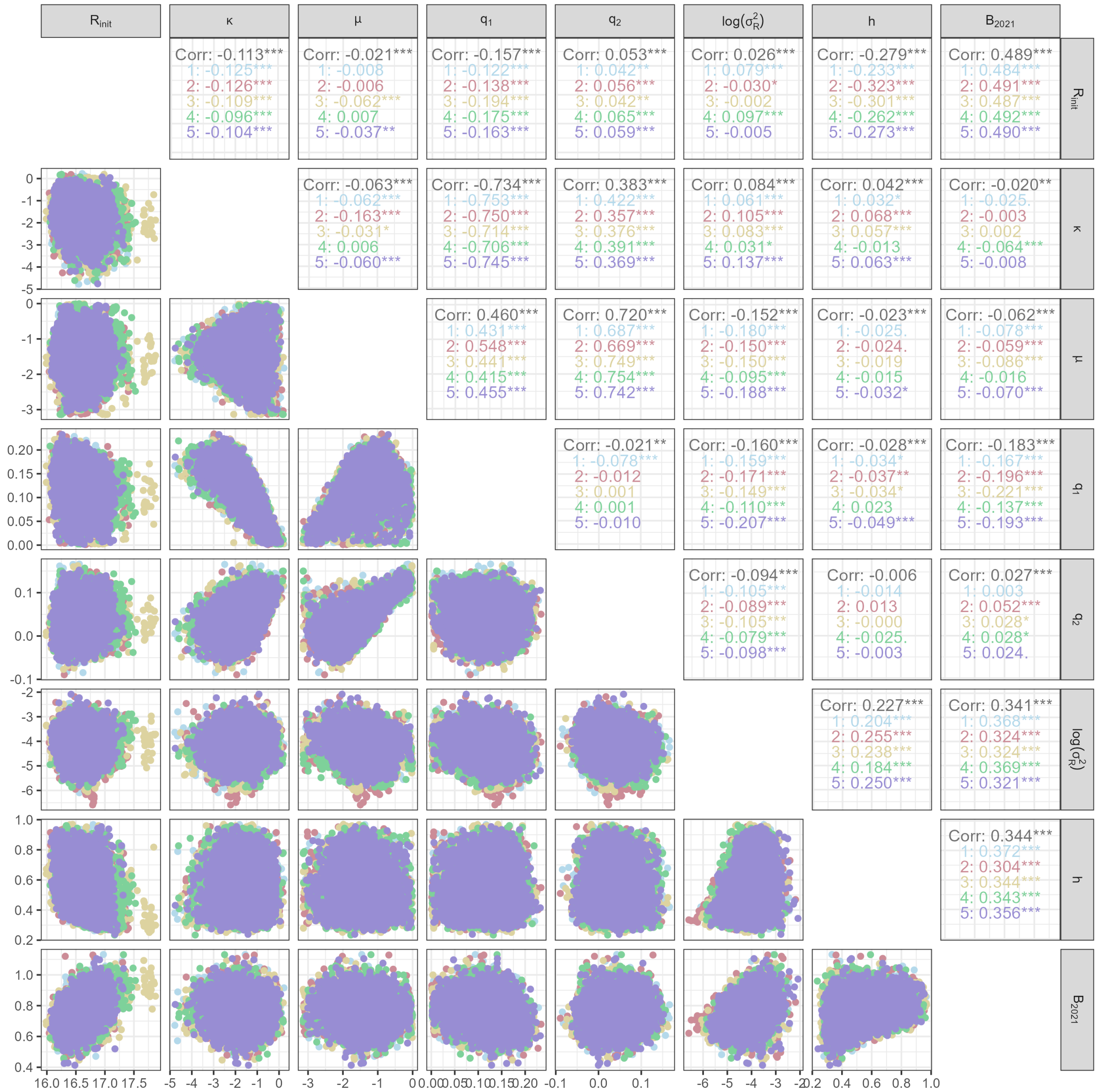


Figure B.72: Correlation plot of MCMC chains for mud bugs scenario 7. Colours distinguish chain and associated correlation.

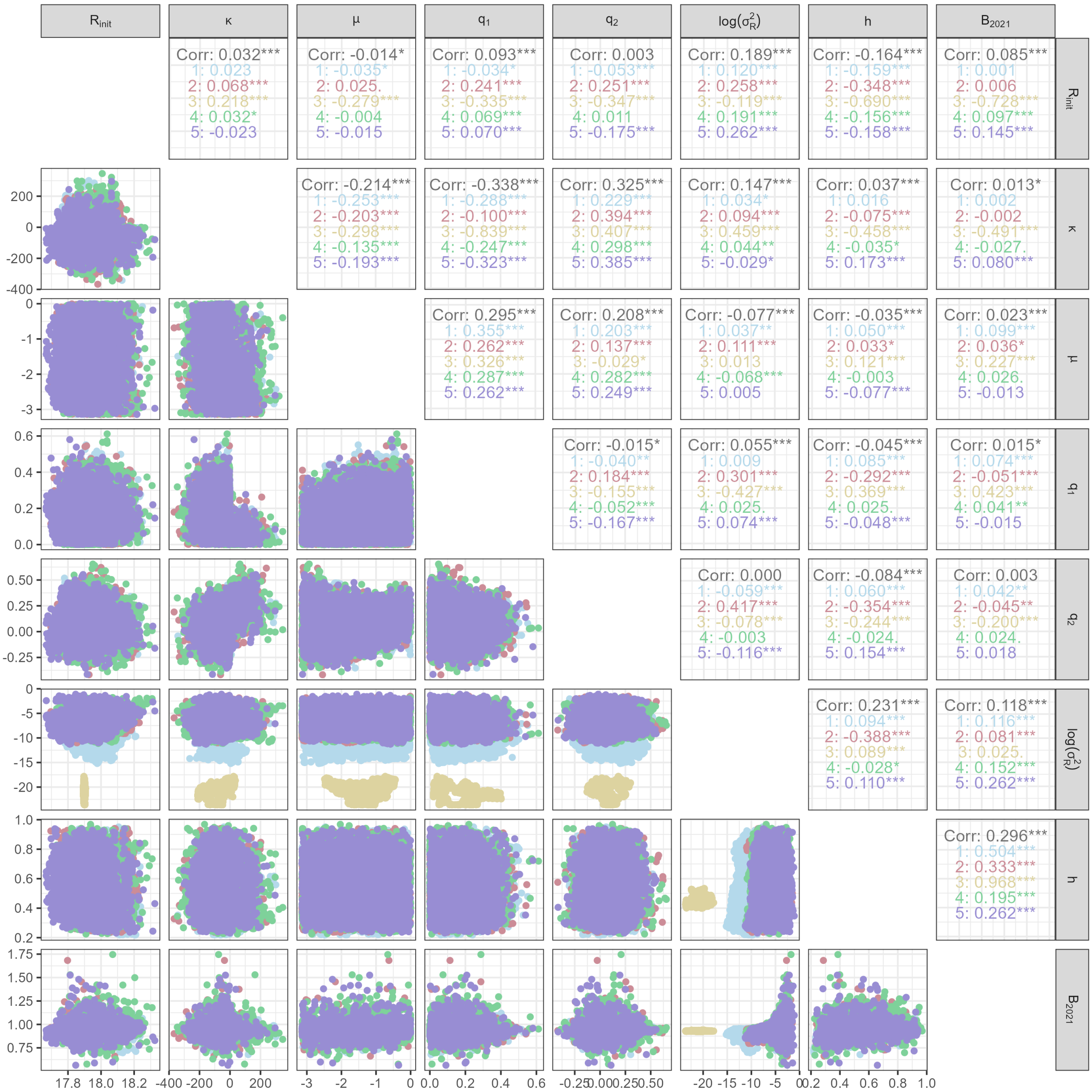


Figure B.73: Correlation plot of MCMC chains for mud bugs scenario 8. Colours distinguish chain and associated correlation.

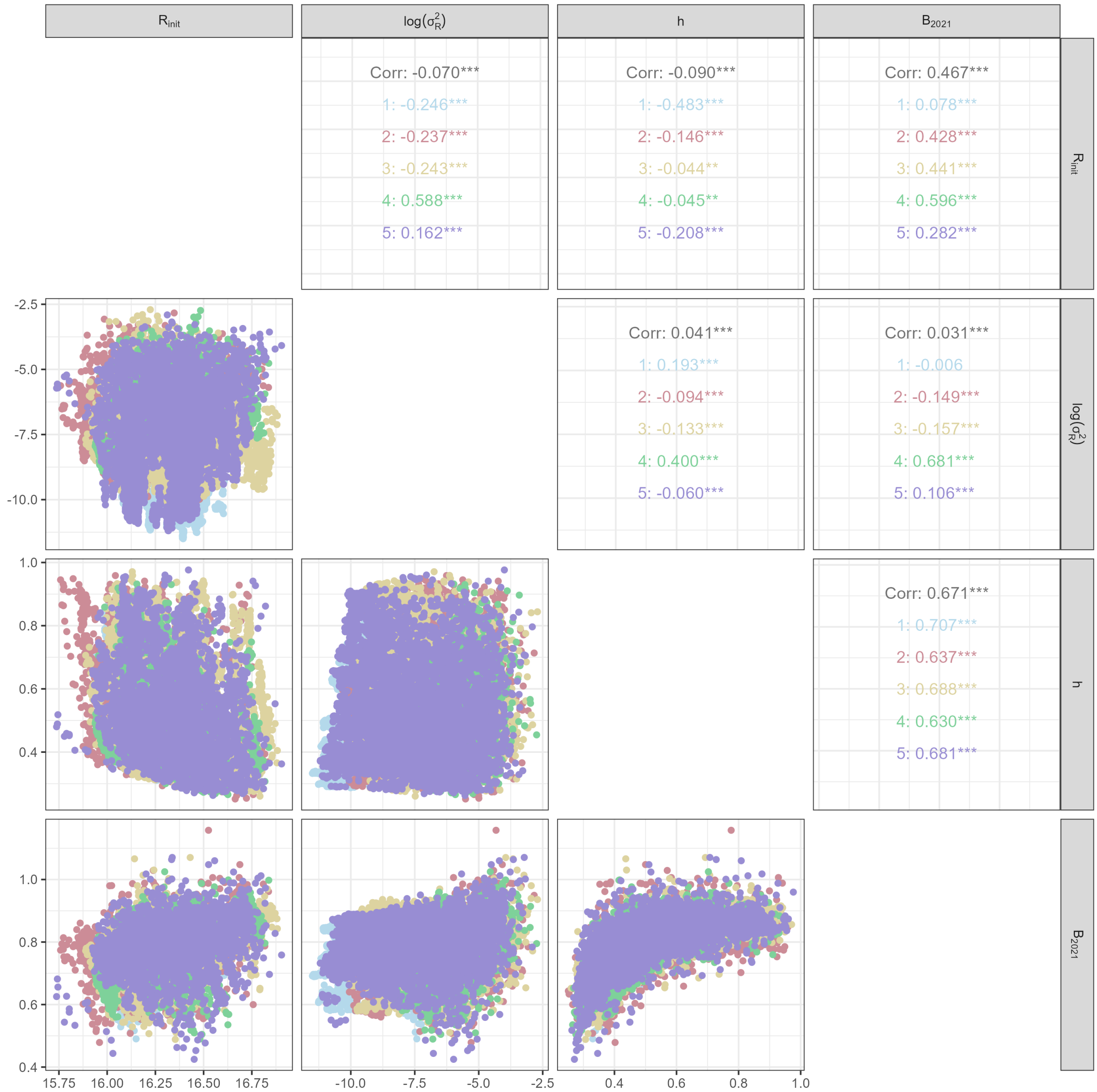


Figure B.74: Correlation plot of MCMC chains for mud bugs scenario 9. Colours distinguish chain and associated correlation.

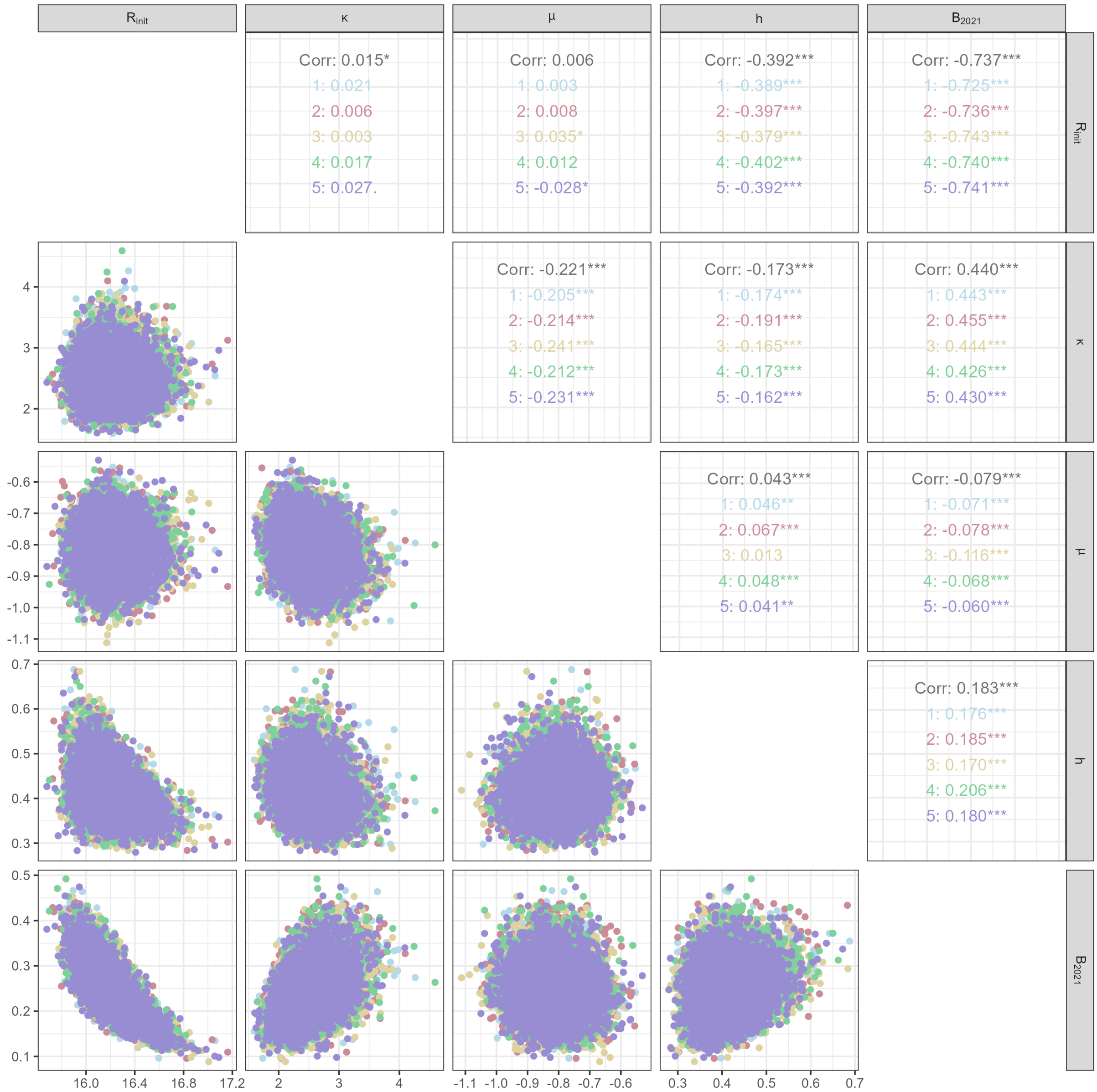


Figure B.75: Correlation plot of MCMC chains for mud bugs scenario 10. Colours distinguish chain and associated correlation.

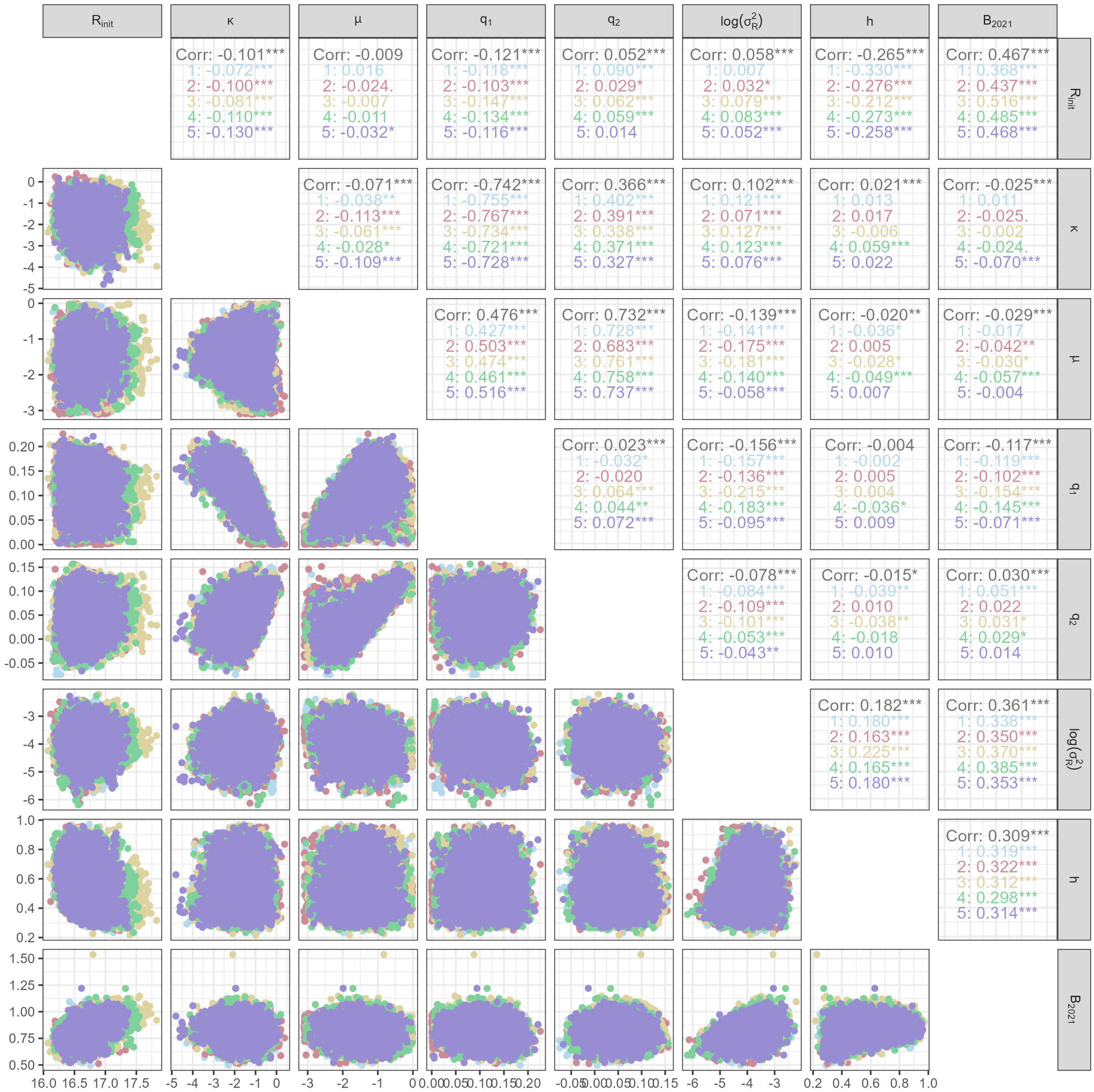


Figure B.76: Correlation plot of MCMC chains for mud bugs scenario 11. Colours distinguish chain and associated correlation.

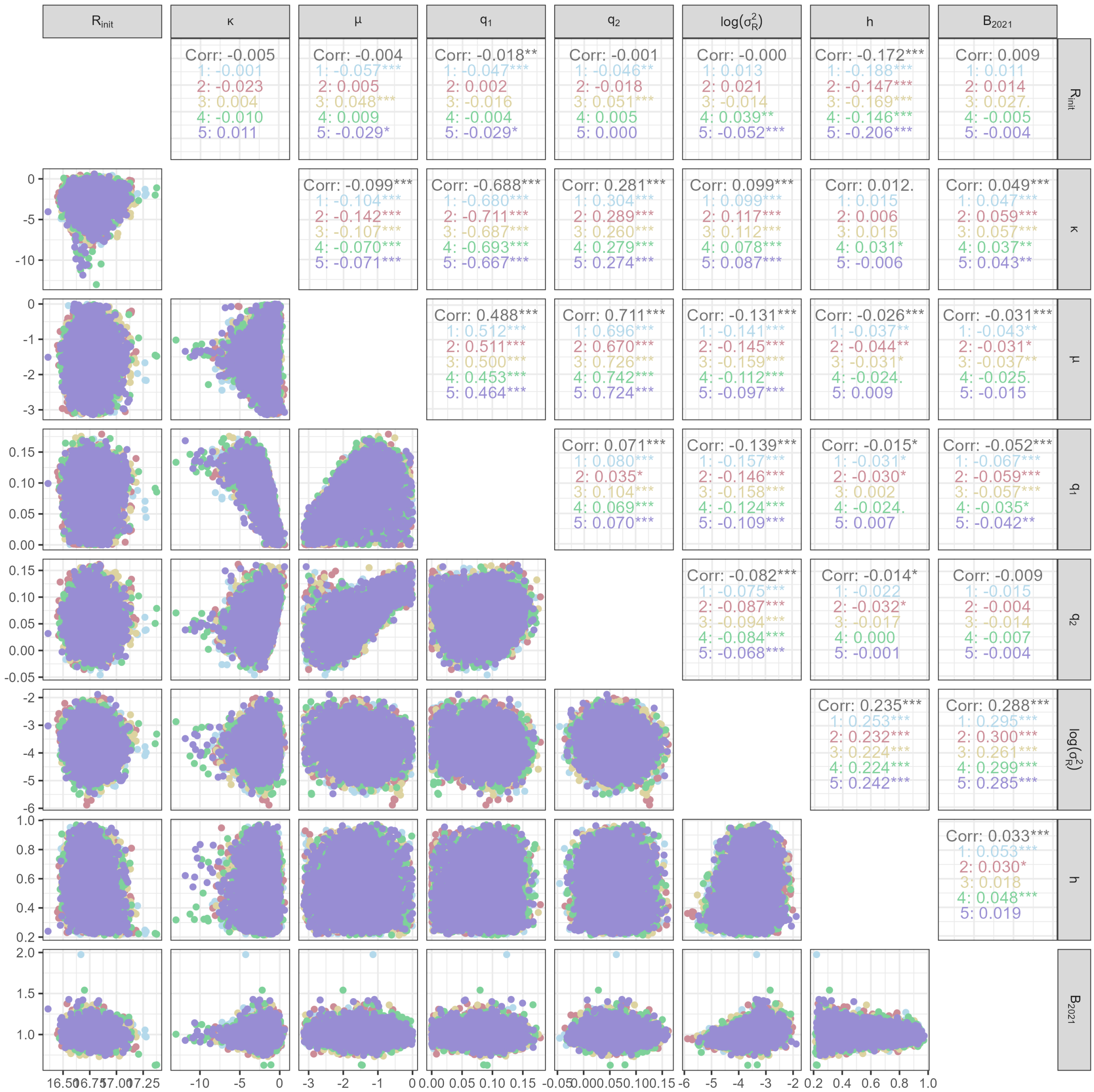


Figure B.77: Correlation plot of MCMC chains for mud bugs scenario 12. Colours distinguish chain and associated correlation.

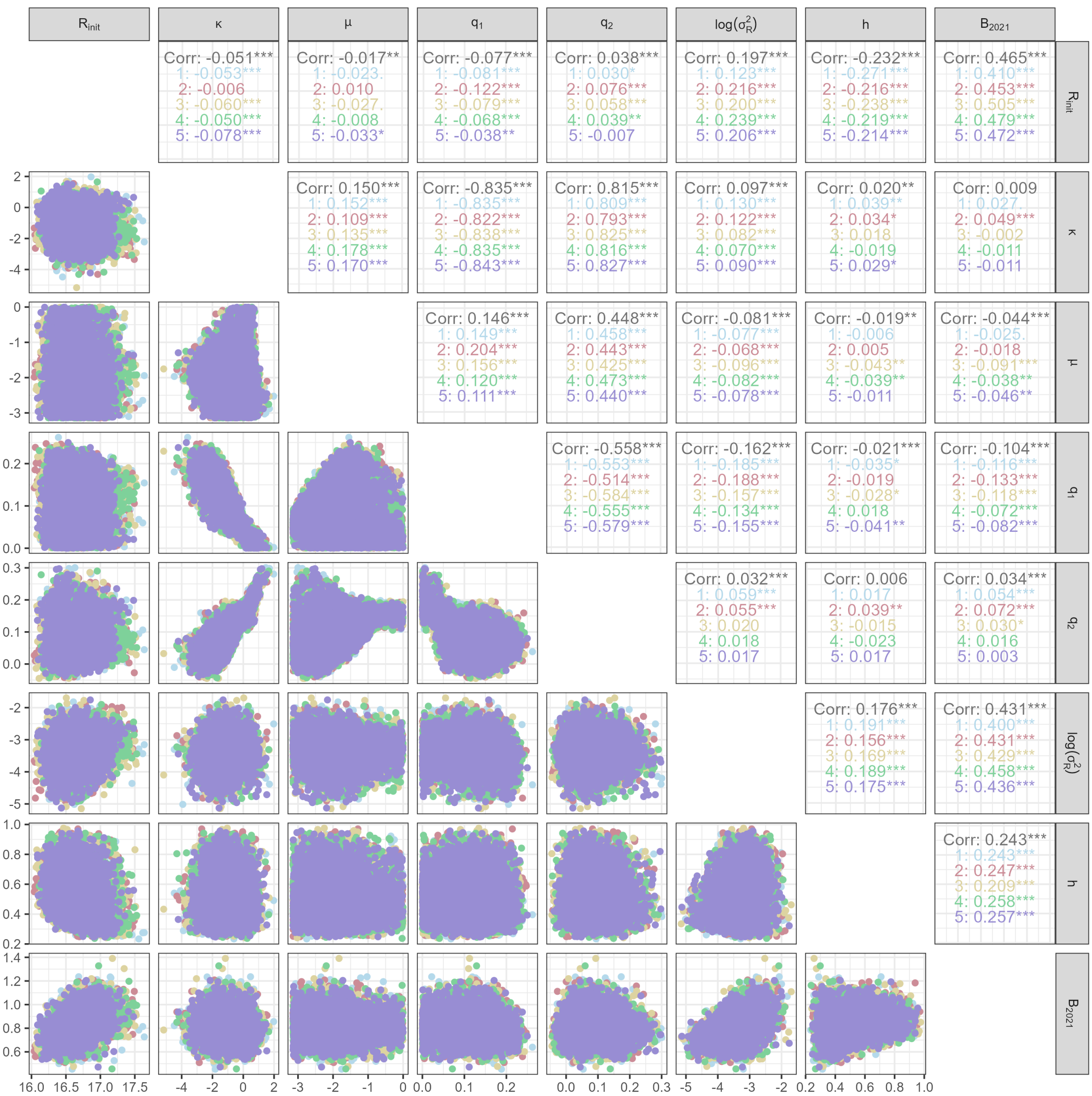


Figure B.78: Correlation plot of MCMC chains for mud bugs scenario 13. Colours distinguish chain and associated correlation.

B.1.4 Potential scale reduction factor

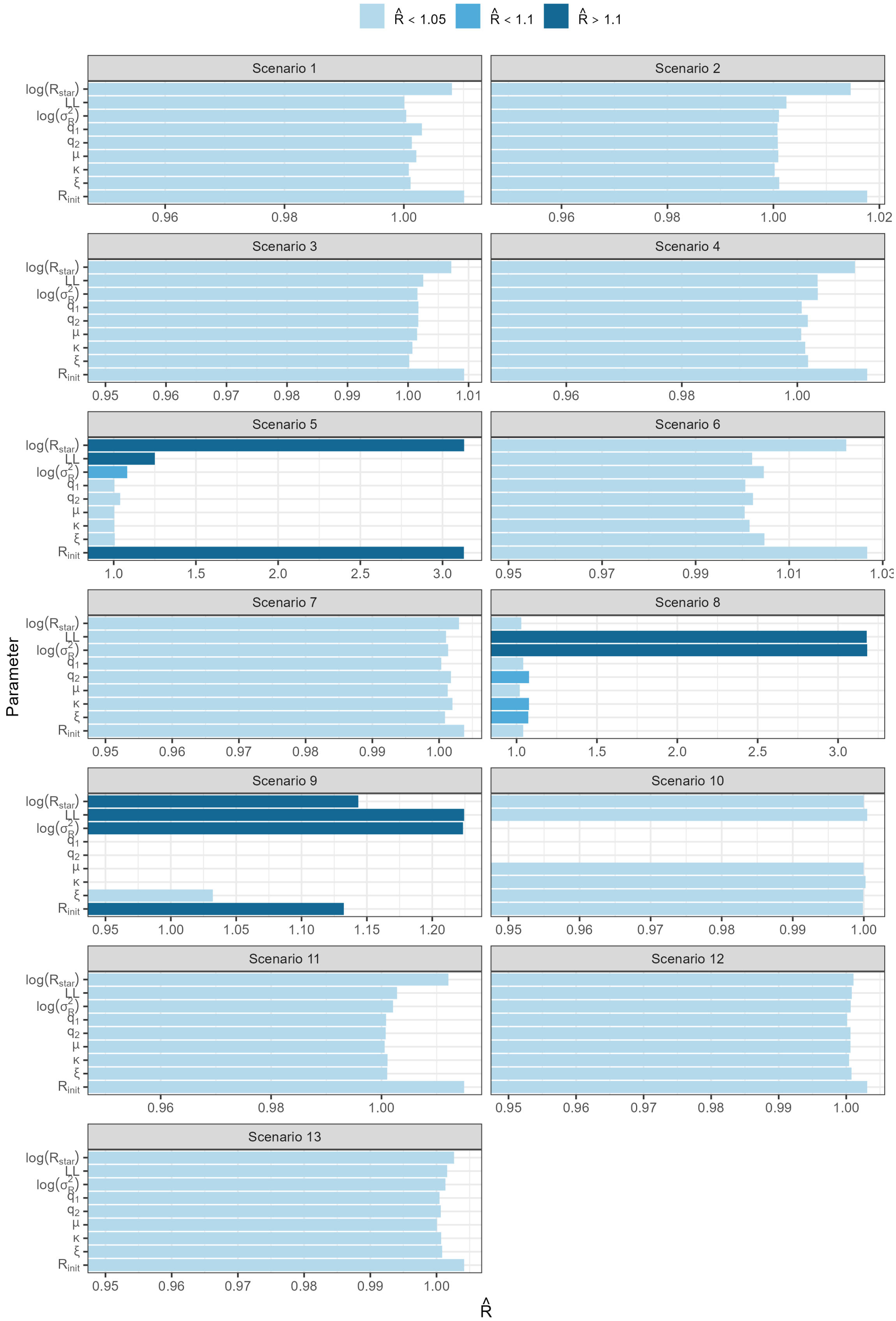


Figure B.79: Potential scale reduction factor, $\hat{R}$, to diagnose sand bug model convergence. Model is likely converged if $\hat{R} < 1.05$. Scenarios 1, 2, 3, 4, 6, 7, 11, 12 and 13 were considered robust

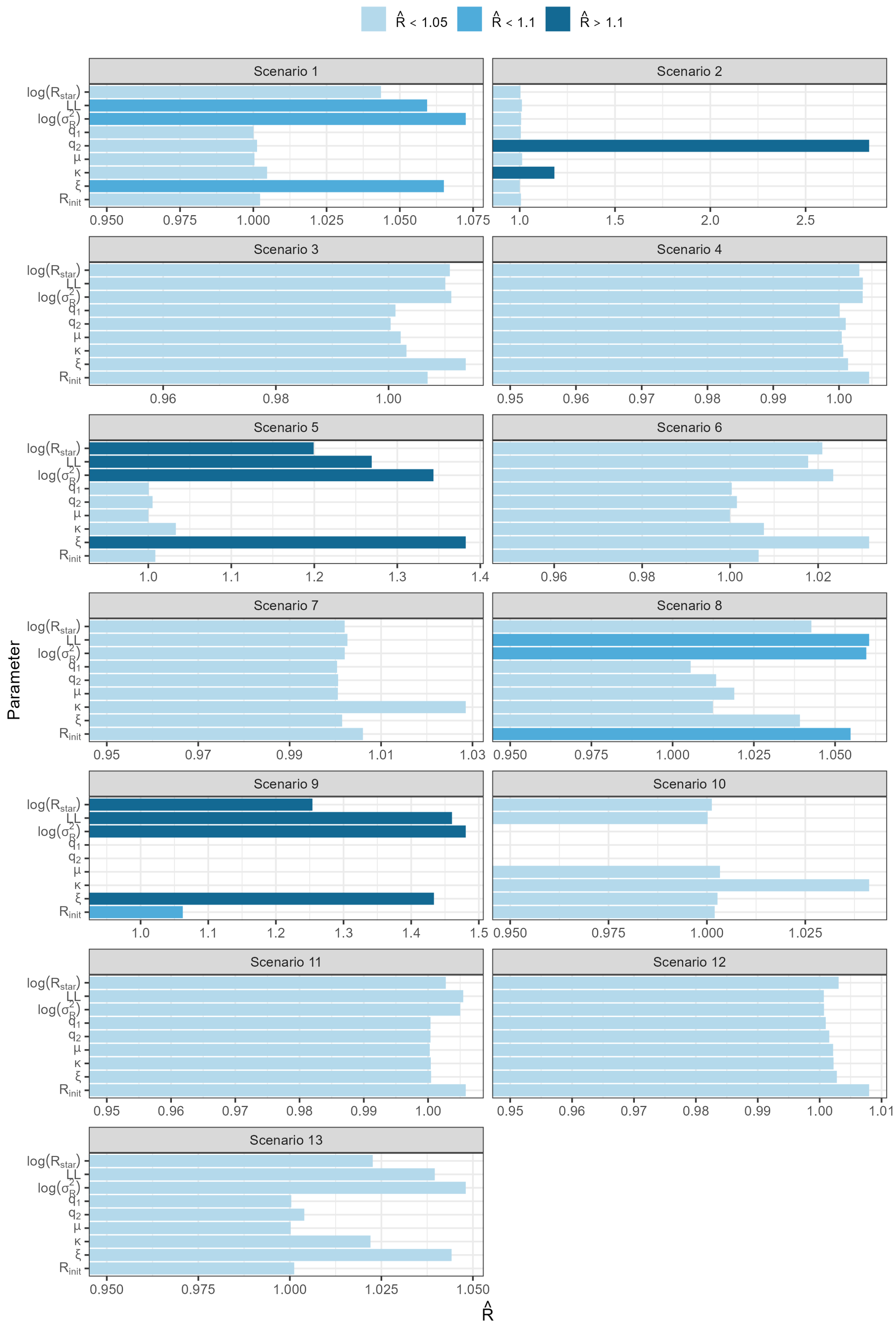


Figure B.80: Potential scale reduction factor, $\hat{R}$, to diagnose mud bug model convergence. Model is likely converged if $\hat{R} < 1.05$. Scenarios 4, 7, 10, 11 and 12 were considered robust

B.2 Scenarios Outputs

Scenarios 1, 2, 3, 4, 6, 7, 11, 12 and 13 were considered to have a high probability of convergence for sand bugs. Scenario 5 for sand bugs had high $\hat{R}$ for the parameters R_{init}, $\log R^*$ and, as a result, the likelihood (Figure B.79). Scenario 8 for sand bugs high $\hat{R}$ for the parameters $\log \sigma_R$ and, as a result, the likelihood (Figure B.79). Scenario 9 for sand bugs had high $\hat{R}$ for the parameters R_{init}, $\log \sigma_R$, $\log R^*$ and, as a result, the likelihood (Figure B.79). Scenario 10 for sand bugs had a stock trajectory not supported by catch and catch rate data. These effects can also be noted in the posterior density plots, trace plots and correlation plots (see Sections B.1.1, B.1.2 and B.1.3).

Scenarios 4, 7, 10, 11 and 12 were considered to have a high probability of convergence for mud bugs. Scenario 1 for mud bugs had high $\hat{R}$ for the parameters ξ, $\log \sigma_R$ and, as a result, the likelihood (Figure B.80). Scenario 2 for mud bugs had high $\hat{R}$ for the parameters κ and μ (Figure B.80). Scenario 5 for mud bugs had high $\hat{R}$ for the parameters ξ, $\log \sigma_R$, $\log R^*$ and, as a result, the likelihood (Figure B.80). Scenario 8 for mud bugs had high $\hat{R}$ for the parameters R_{init}, $\log \sigma_R$ and, as a result, the likelihood (Figure B.80). Scenario 9 for mud bugs had high $\hat{R}$ for the parameters R_{init}, ξ, $\log \sigma_R$, $\log R^*$ and, as a result, the likelihood (Figure B.80). Scenarios 3, 6, 10 and 13 had multi-modal posterior density plots (Figures B.16, B.19, B.23, B.26). These effects can also be noted in the posterior density plots, trace plots and correlation plots (see Sections B.1.1, B.1.2 and B.1.3).

B.2.1 Sensitivity tests

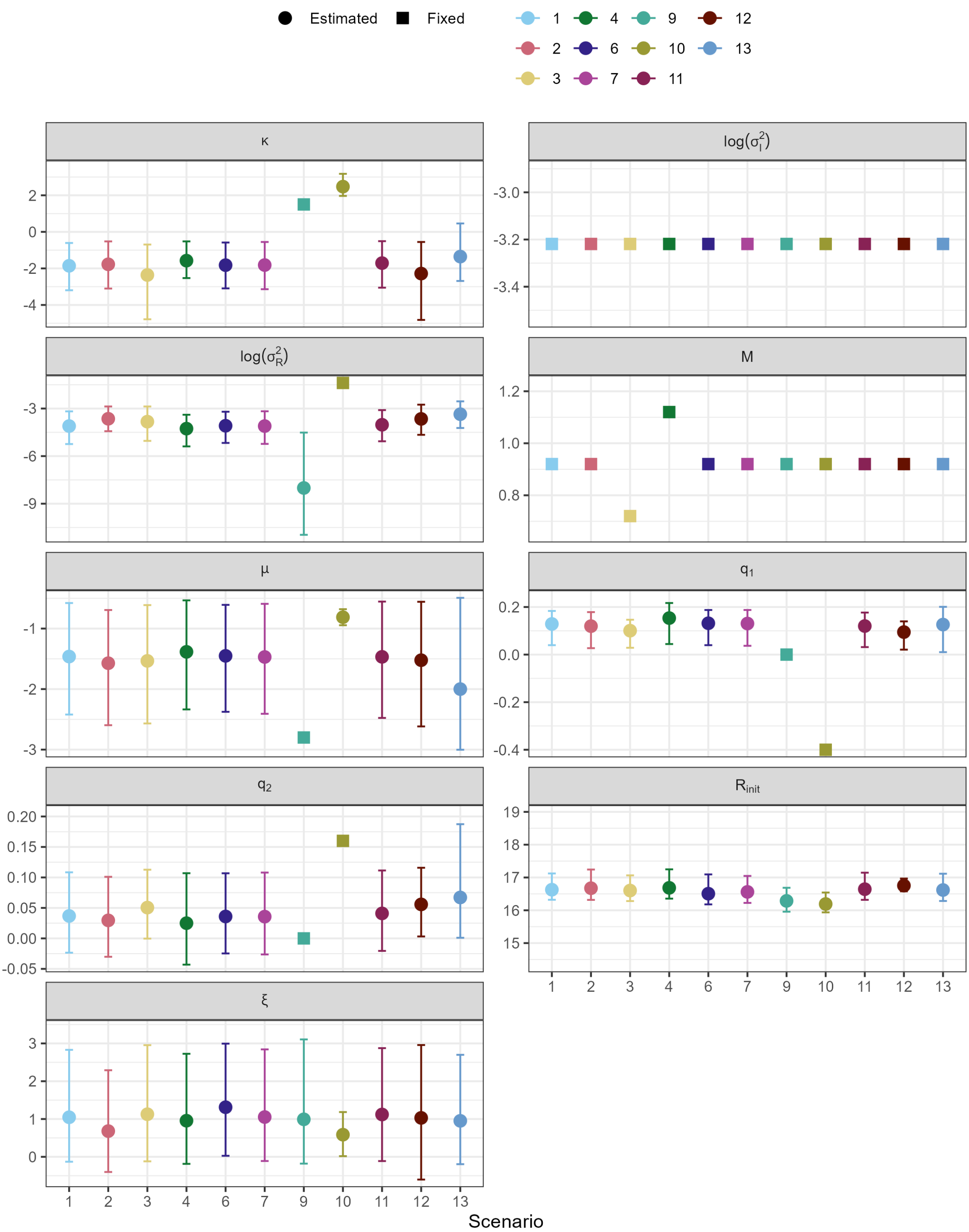


Figure B.81: Comparison of sand bug model parameter estimates from the scenarios with a high probability of convergence

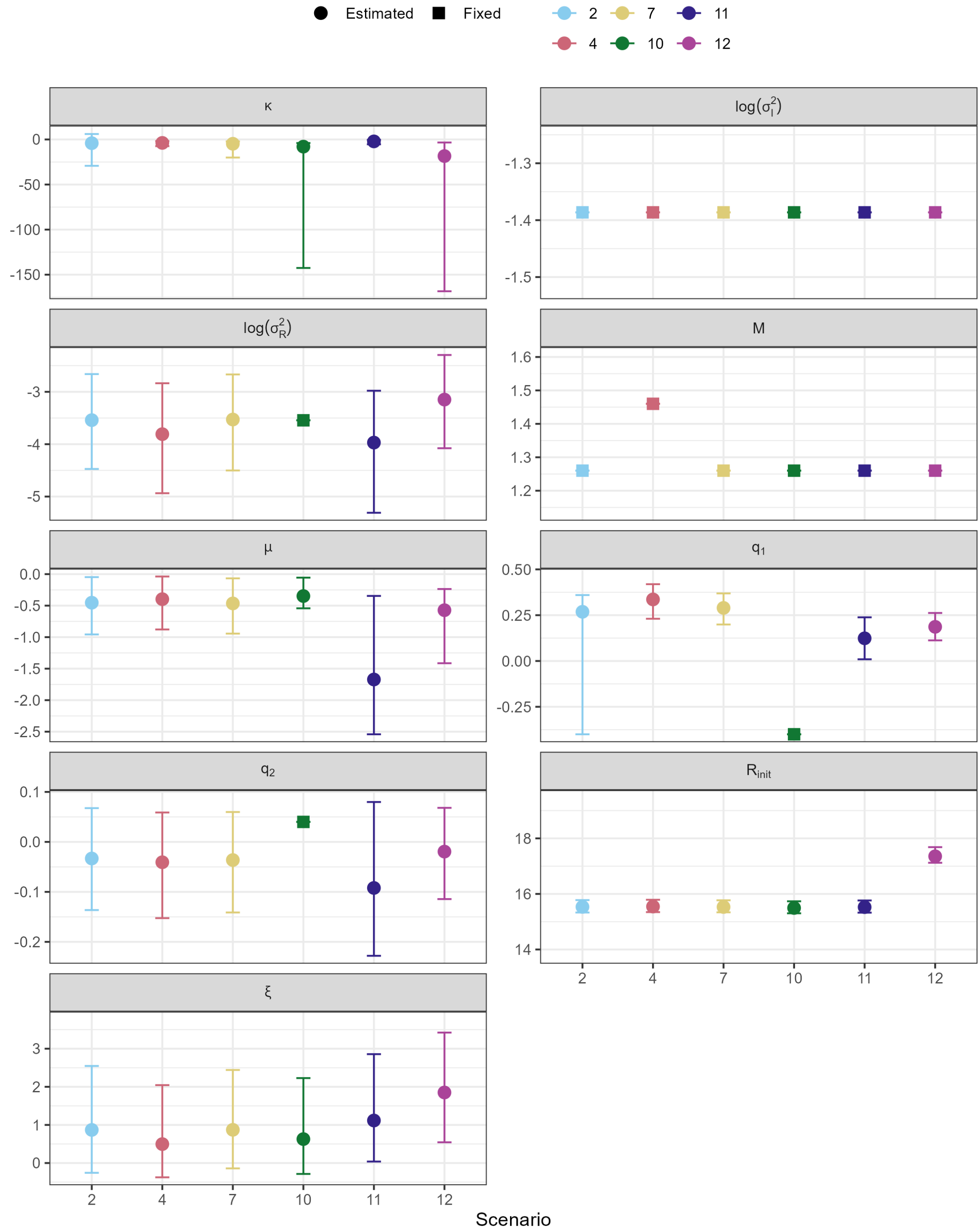


Figure B.82: Comparison of mud bug model parameter estimates from the scenarios with a high probability of convergence

B.2.2 Biomass

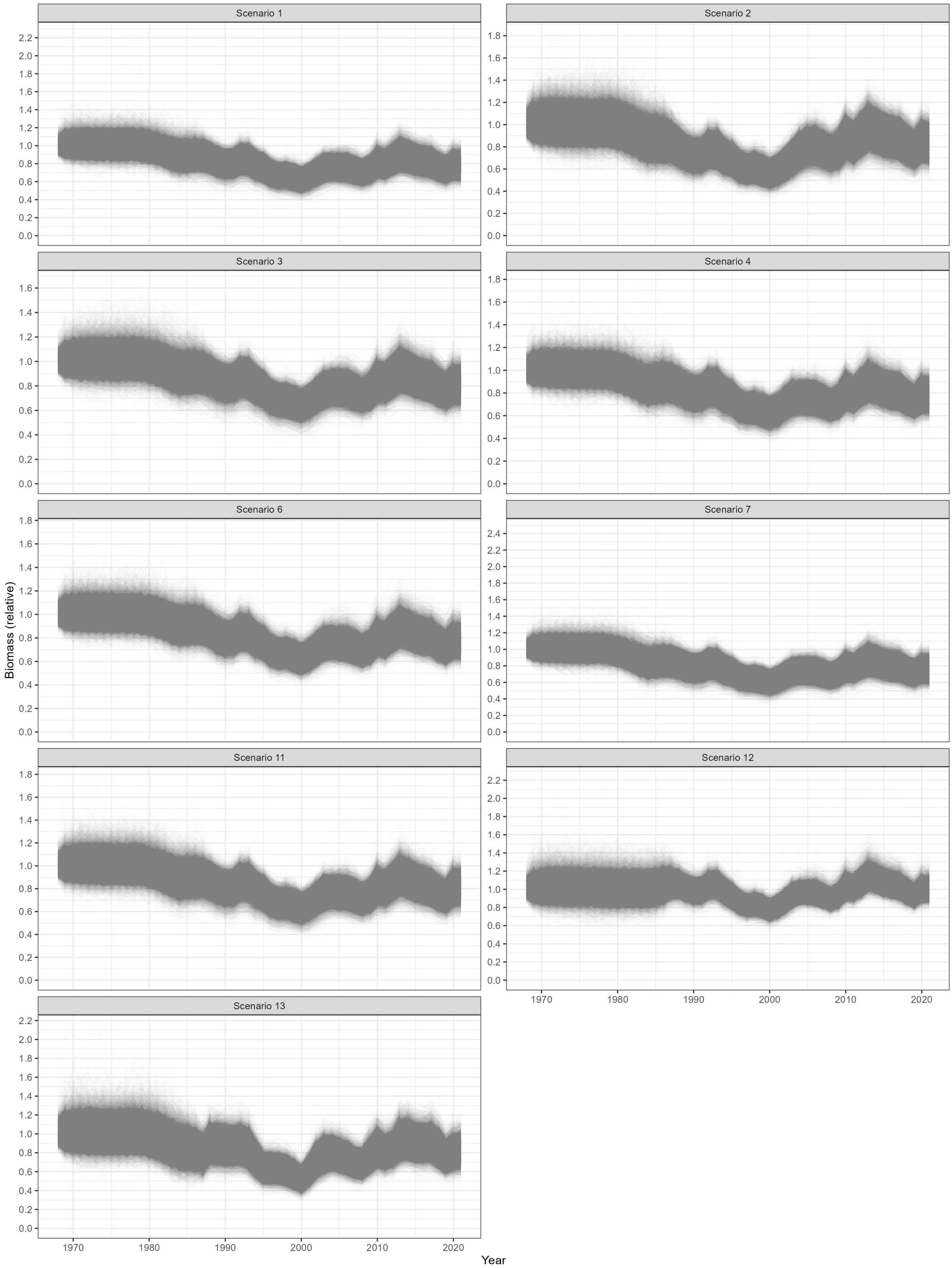


Figure B.83: Predicted stock biomass trajectory relative to unfished, from 1968 to 2021 for sand bugs in the ECOTF

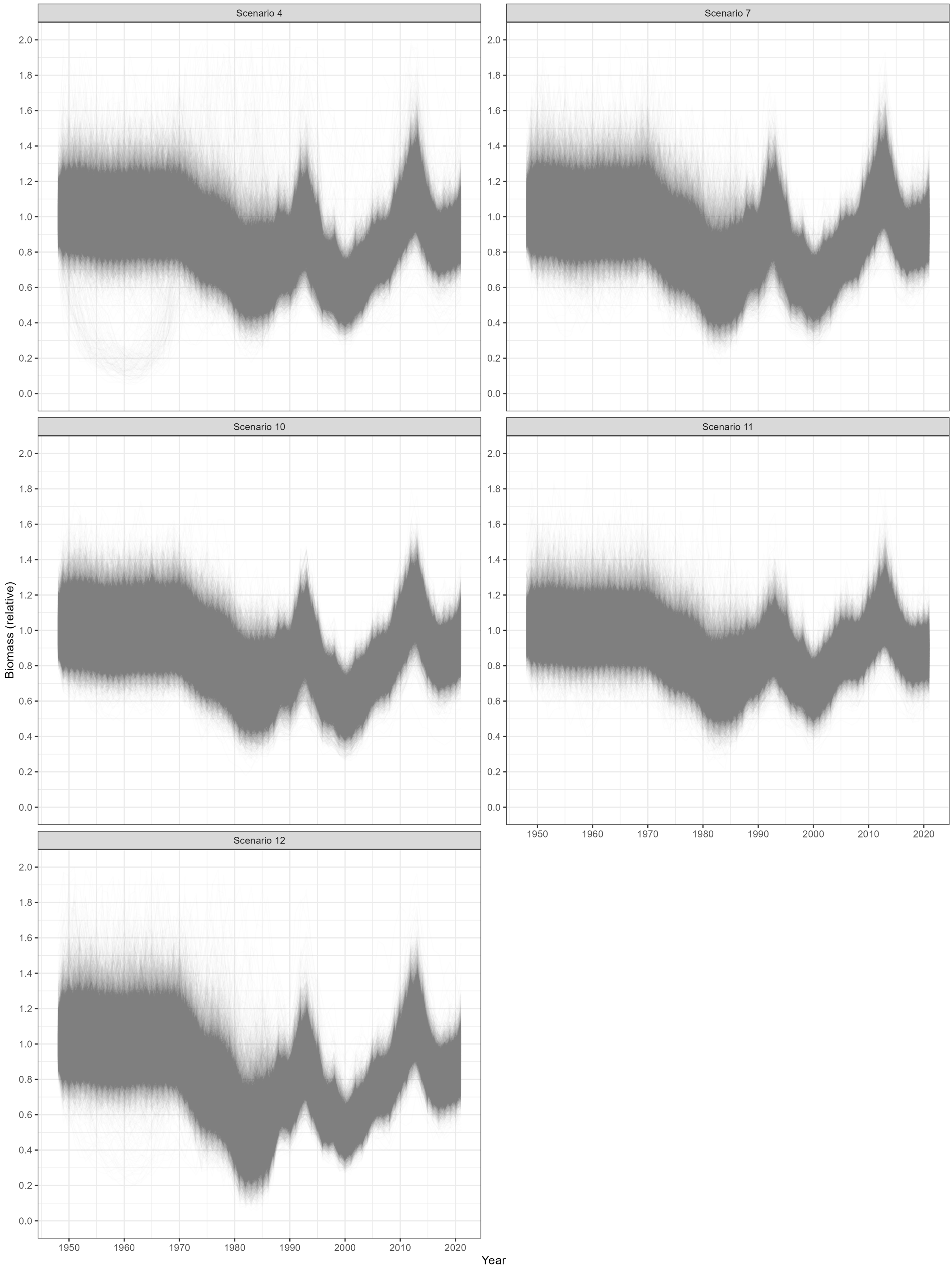


Figure B.84: Predicted stock biomass trajectory relative to unfished, from 1968 to 2021 for mud bugs in the ECOTF.

B.2.3 Abundance indices

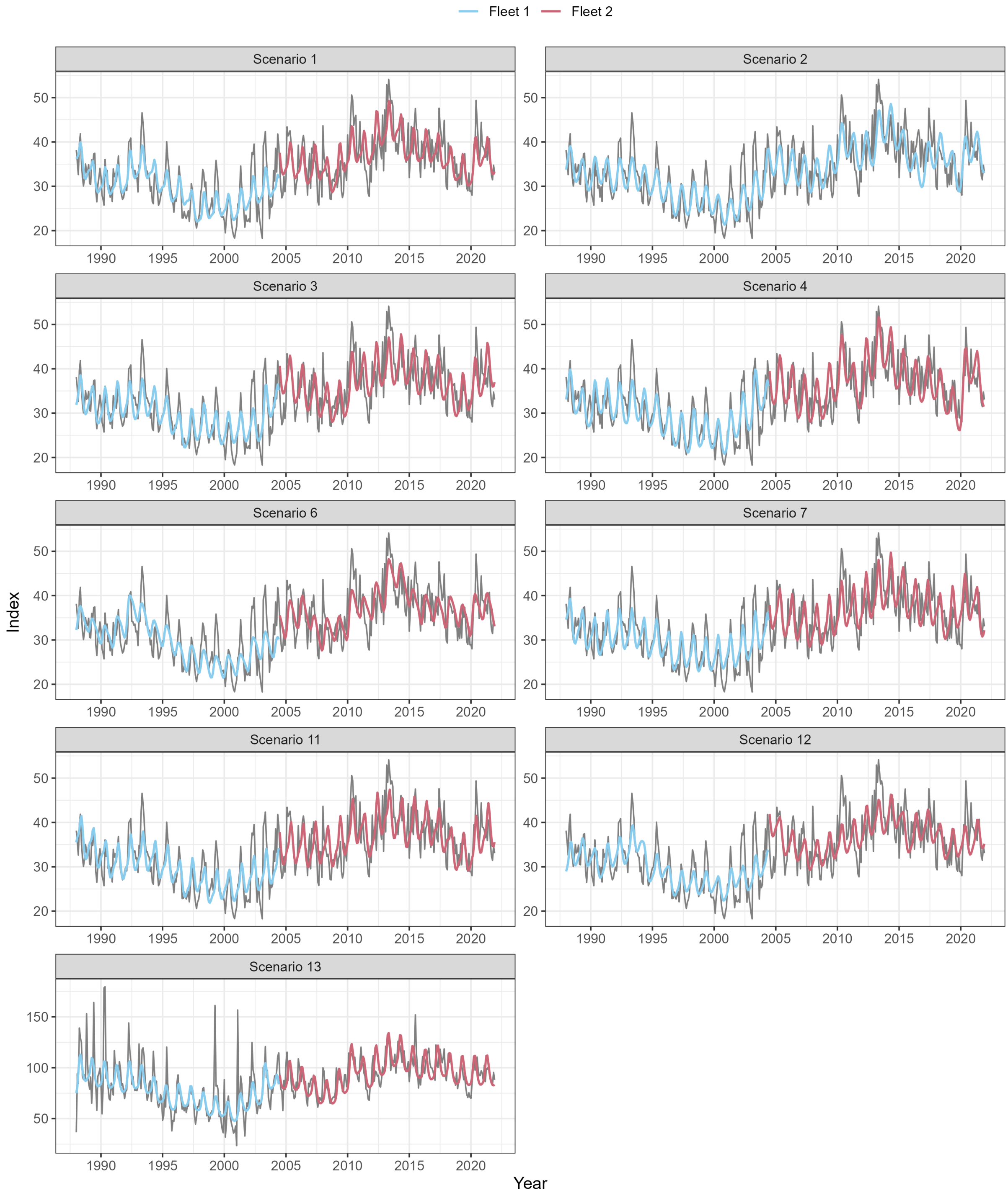


Figure B.85: Model predictions (blue and maroon lines) to commercial catch rates for median trajectory for sand bugs.

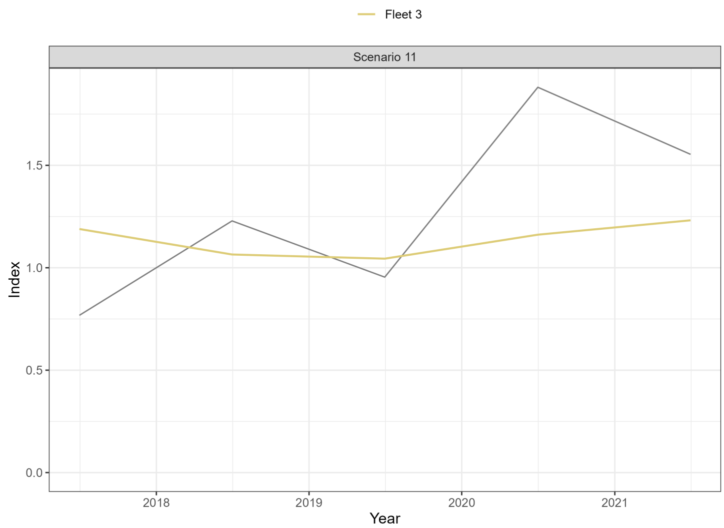


Figure B.86: Model predictions (yellow lines) to survey catch rates for median trajectory for sand bugs Scenario 11.

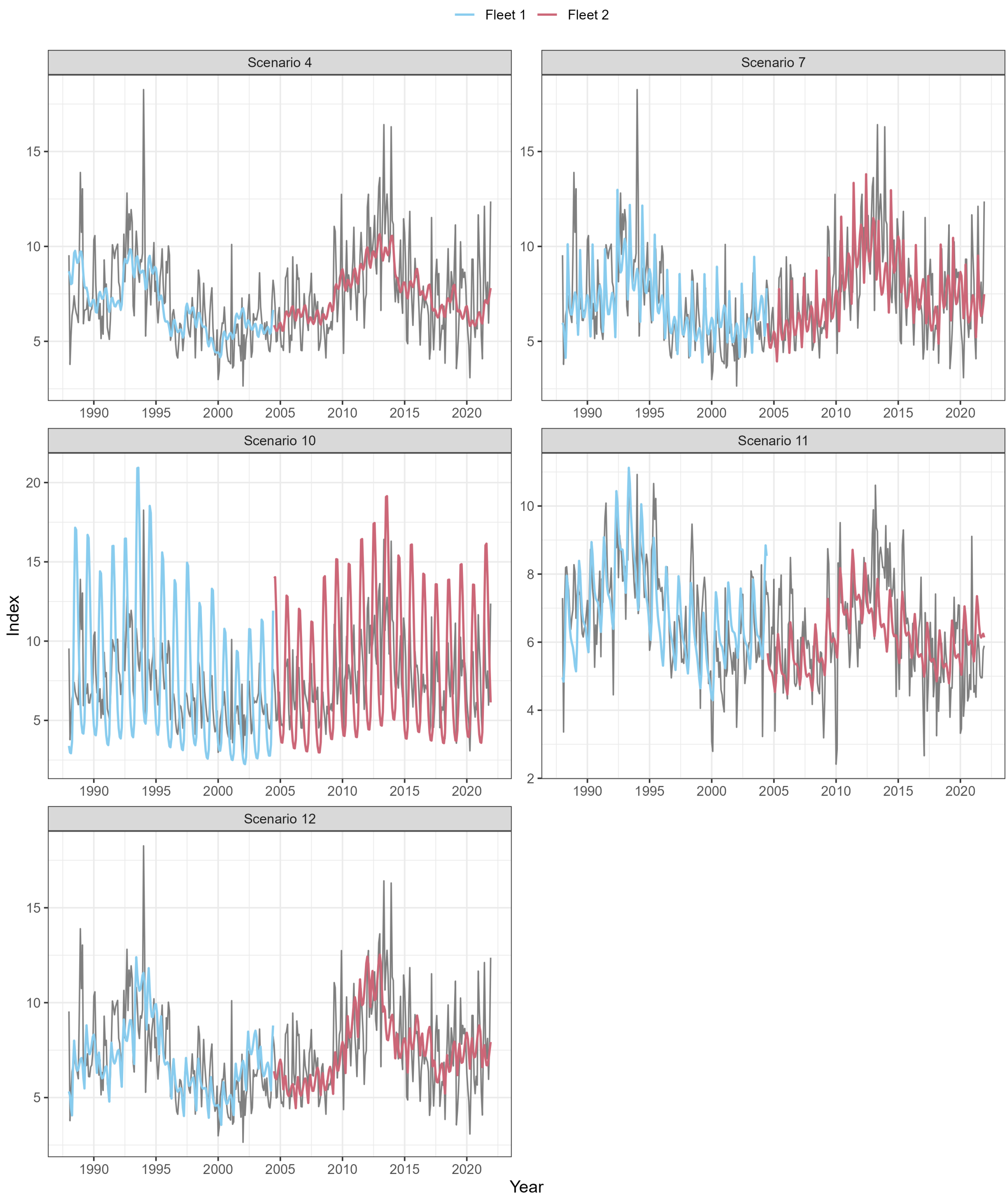


Figure B.87: Model predictions (blue and maroon lines) to commercial catch rates for median trajectory for mud bugs.

B.2.4 Annual aggregated fit

Figure B.88: Model predictions (blue and maroon lines) to commercial catch rates for sand bugs aggregated by year.

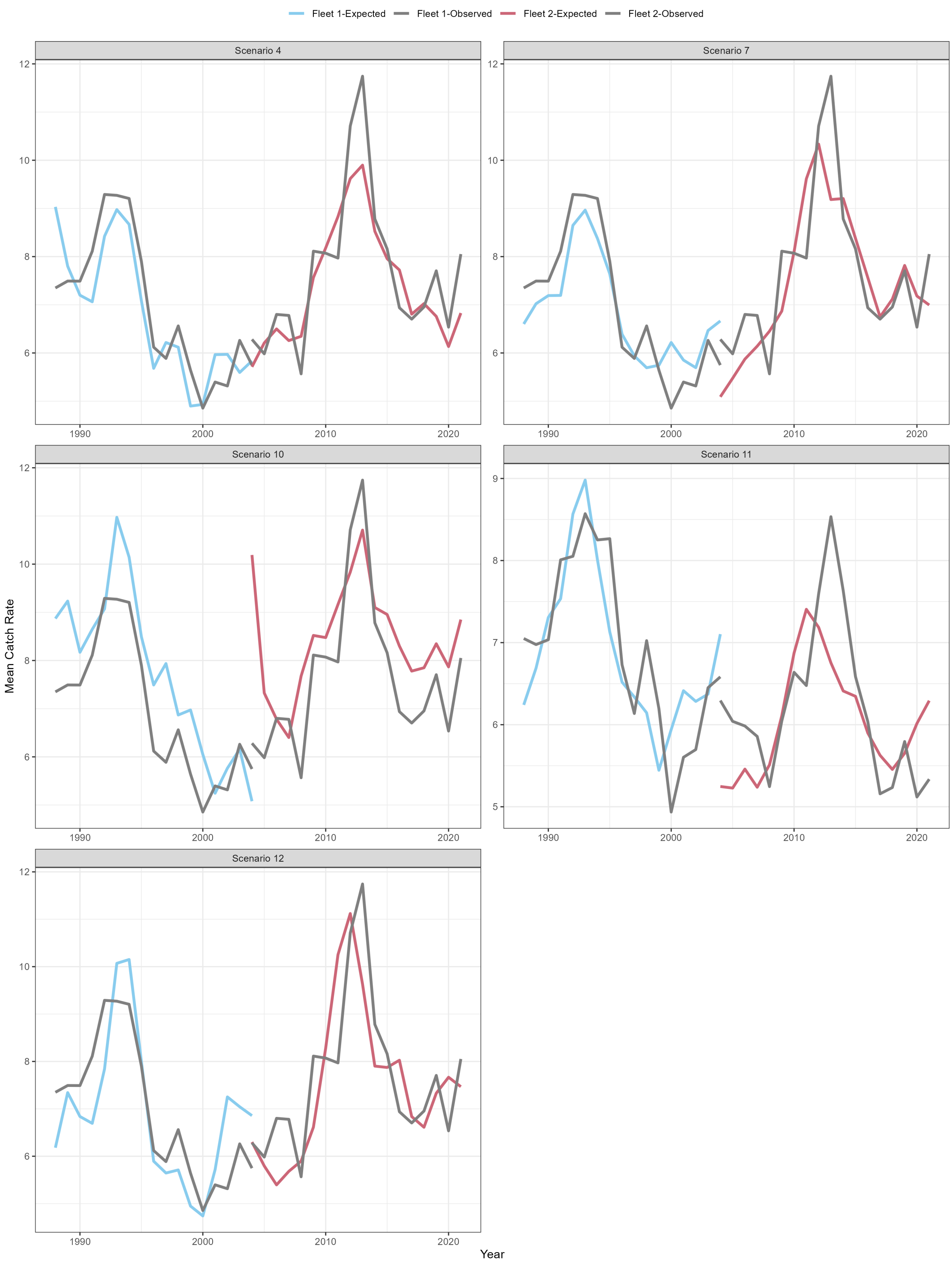


Figure B.89: Model predictions (blue and maroon lines) to commercial catch rates for mud bugs aggregated by year.

B.2.5 Monthly aggregated fit

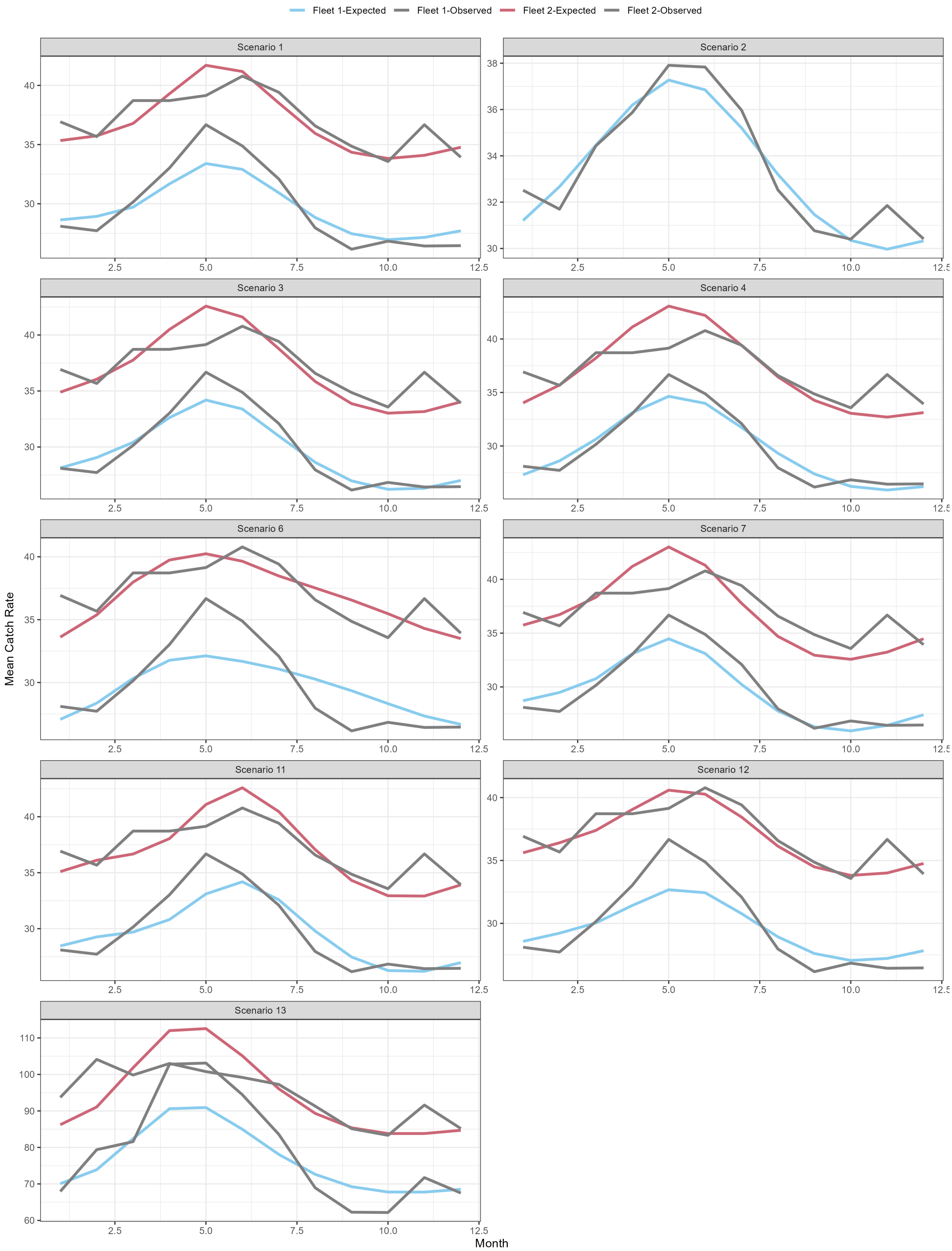


Figure B.90: Model predictions (blue and maroon lines) to commercial catch rates for sand bugs aggregated by month

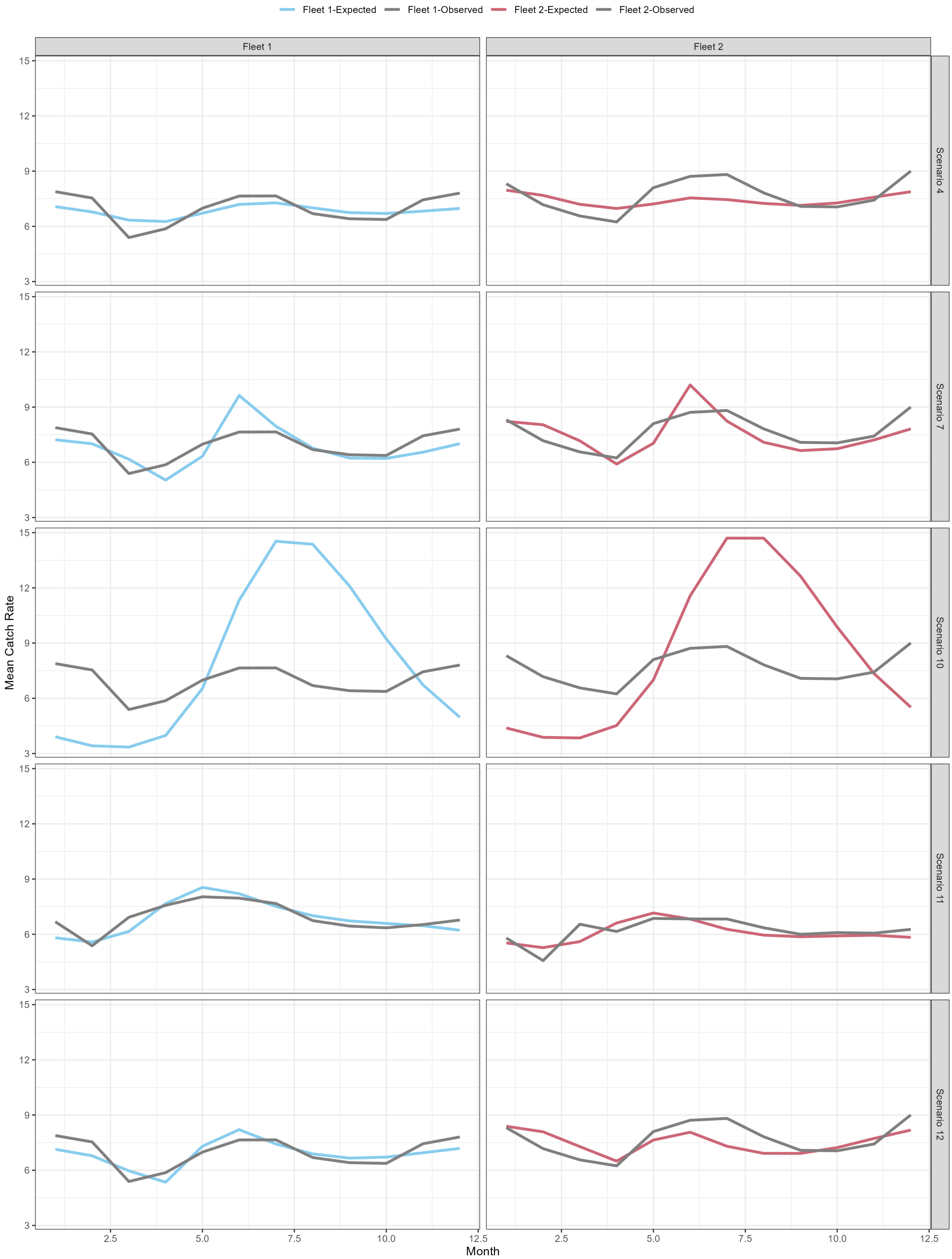


Figure B.91: Model predictions (blue and maroon lines) to commercial catch rates for mud bugs aggregated by month

B.2.6 Stock-recruit curve

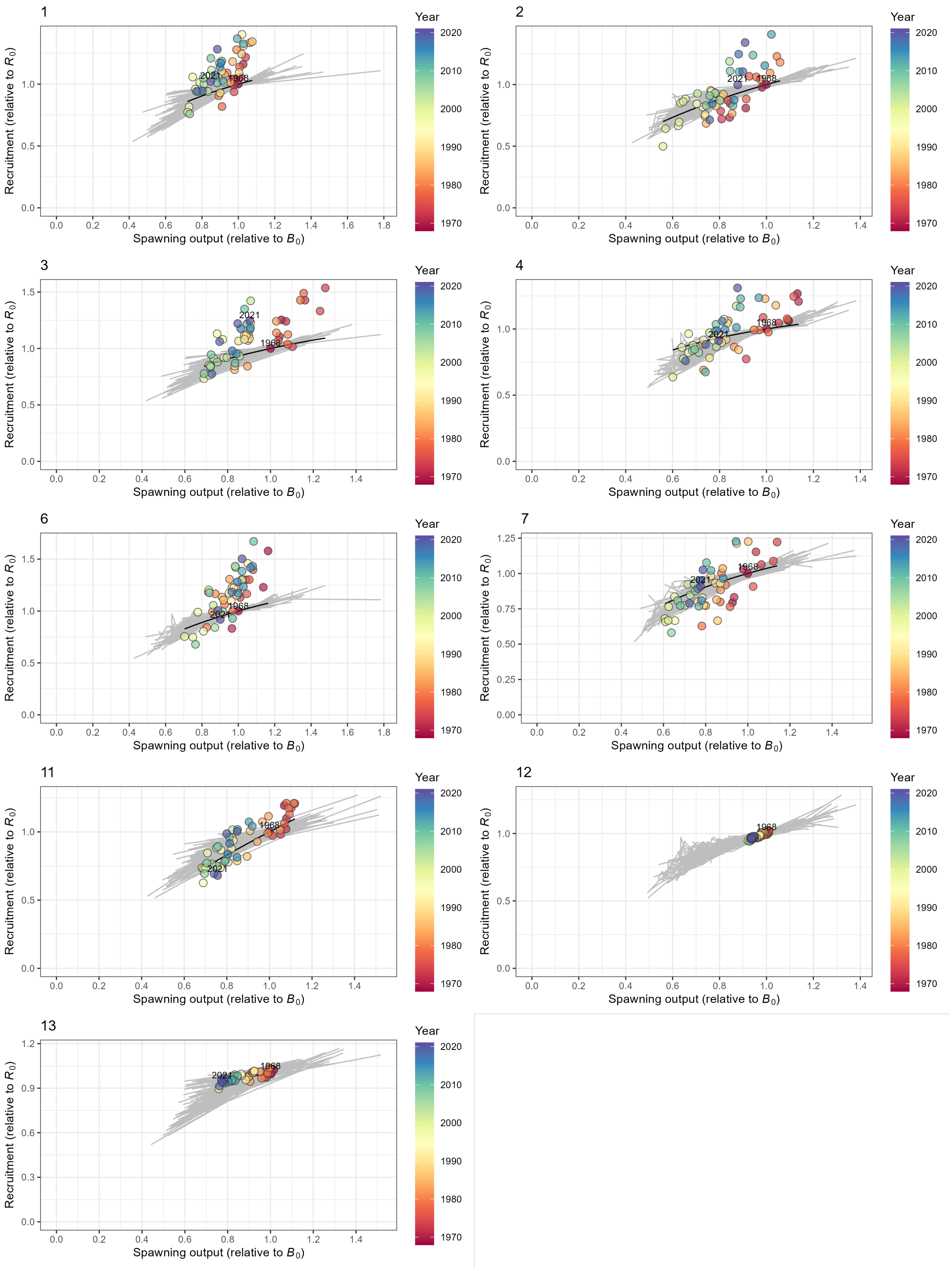


Figure B.92: Stock-recruit curve for median trajectory of sand bug MCMC fit – point colors indicate year, with warmer colors indicating earlier years and cooler colors in showing later years. 1000 samples of MCMC stock-recruitment relationship shown in grey.

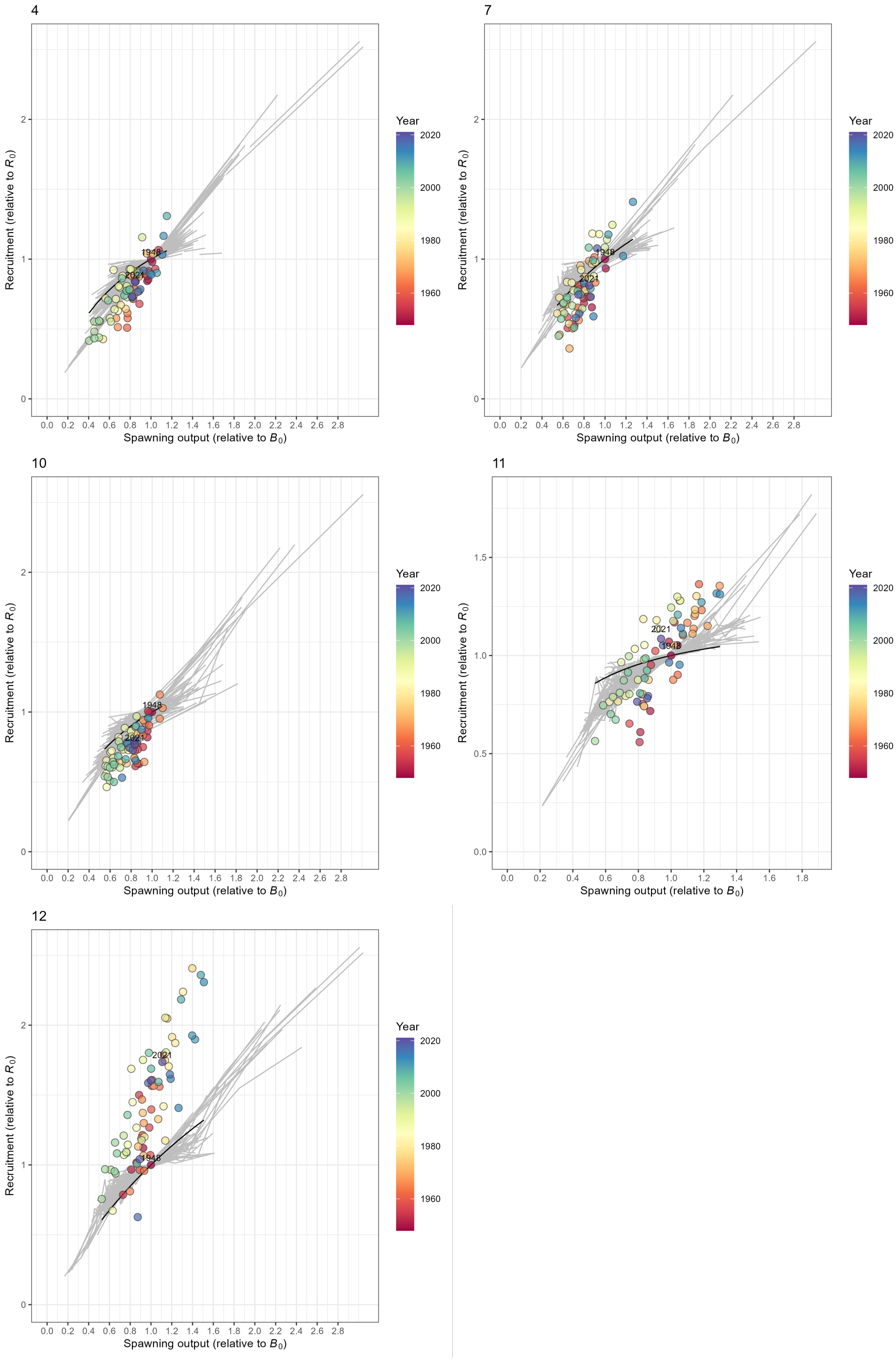


Figure B.93: Stock-recruit curve for median trajectory of mud bug MCMC fit – point colors indicate year, with warmer colors indicating earlier years and cooler colors in showing later years. 1000 samples of MCMC stock-recruitment relationship shown in grey.

B.2.7 Recruitment deviation

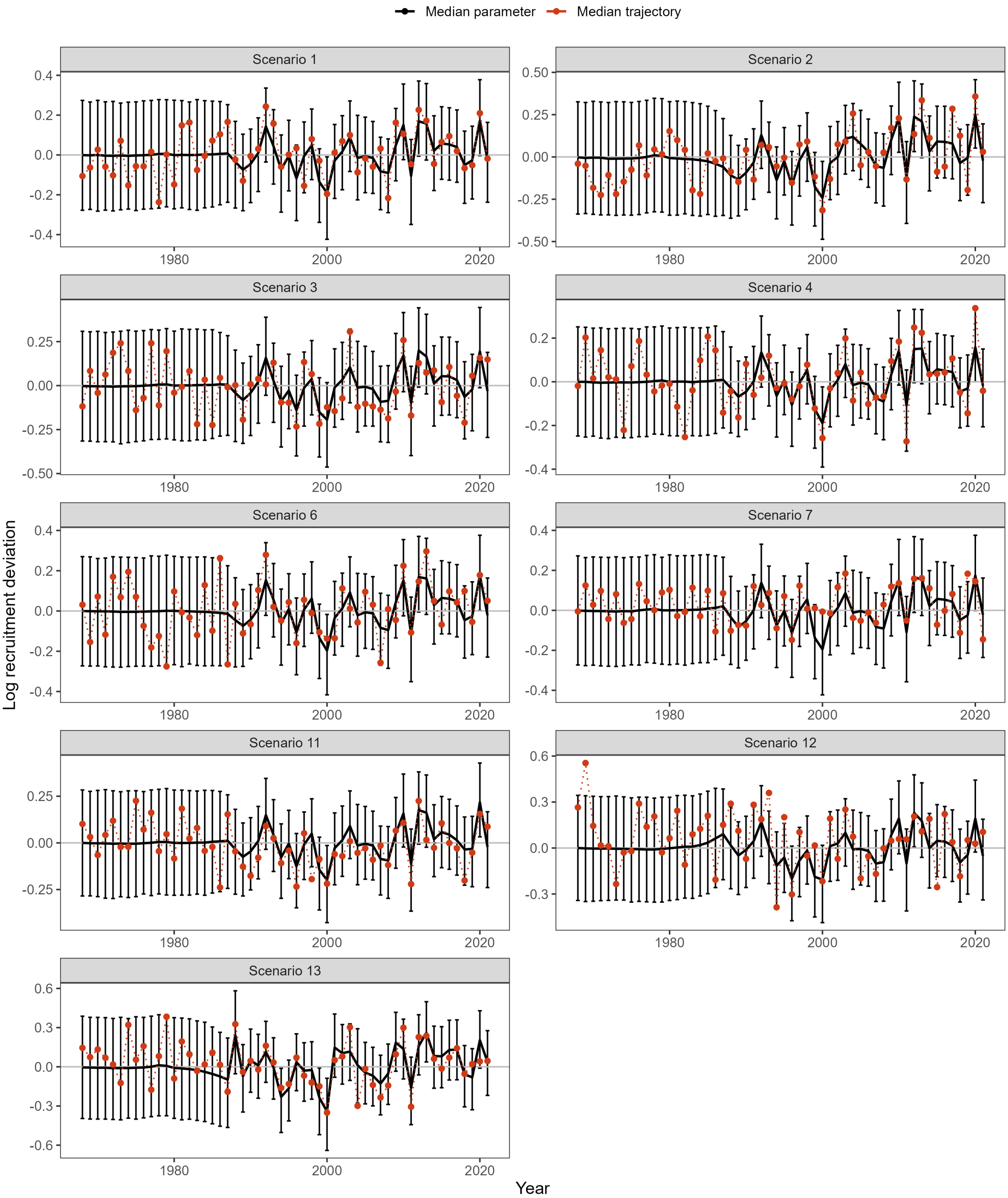


Figure B.94: Recruitment deviations with 95% credible intervals for the sand bug model

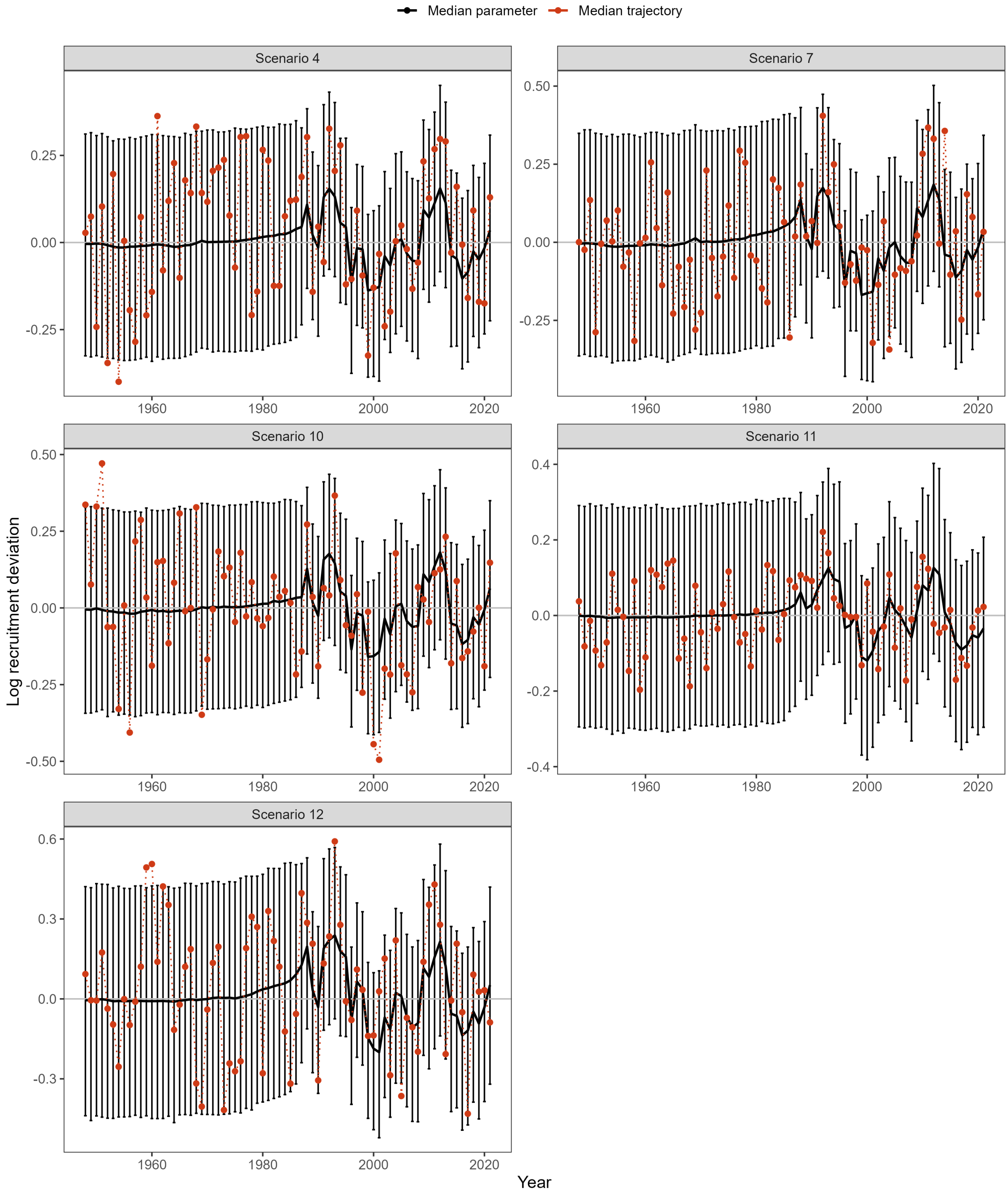


Figure B.95: Recruitment deviations with 95% credible intervals for the mud bug model

B.2.8 Seasonal recruitment

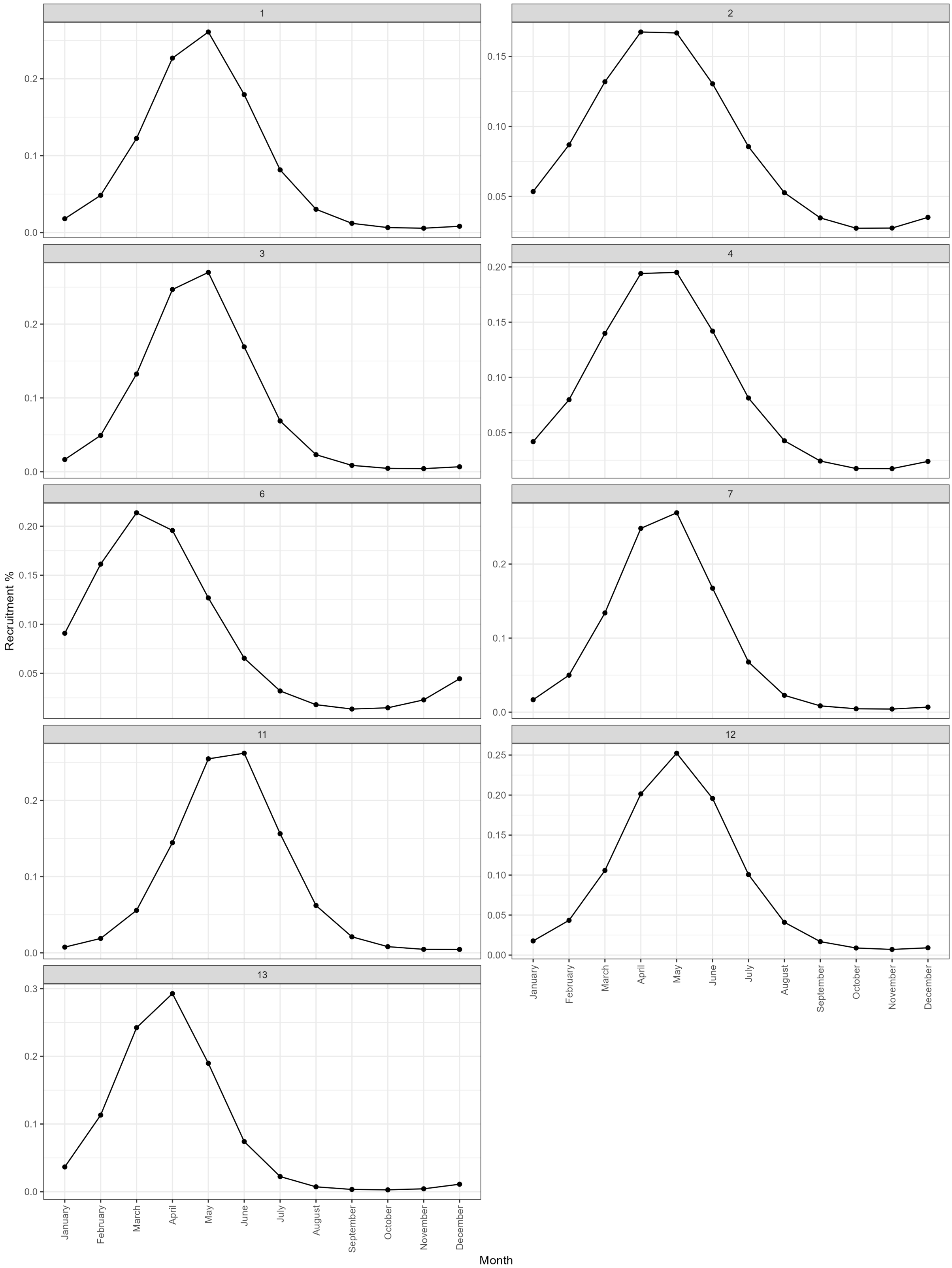


Figure B.96: Seasonal recruitment pattern plot for the sand bug model.

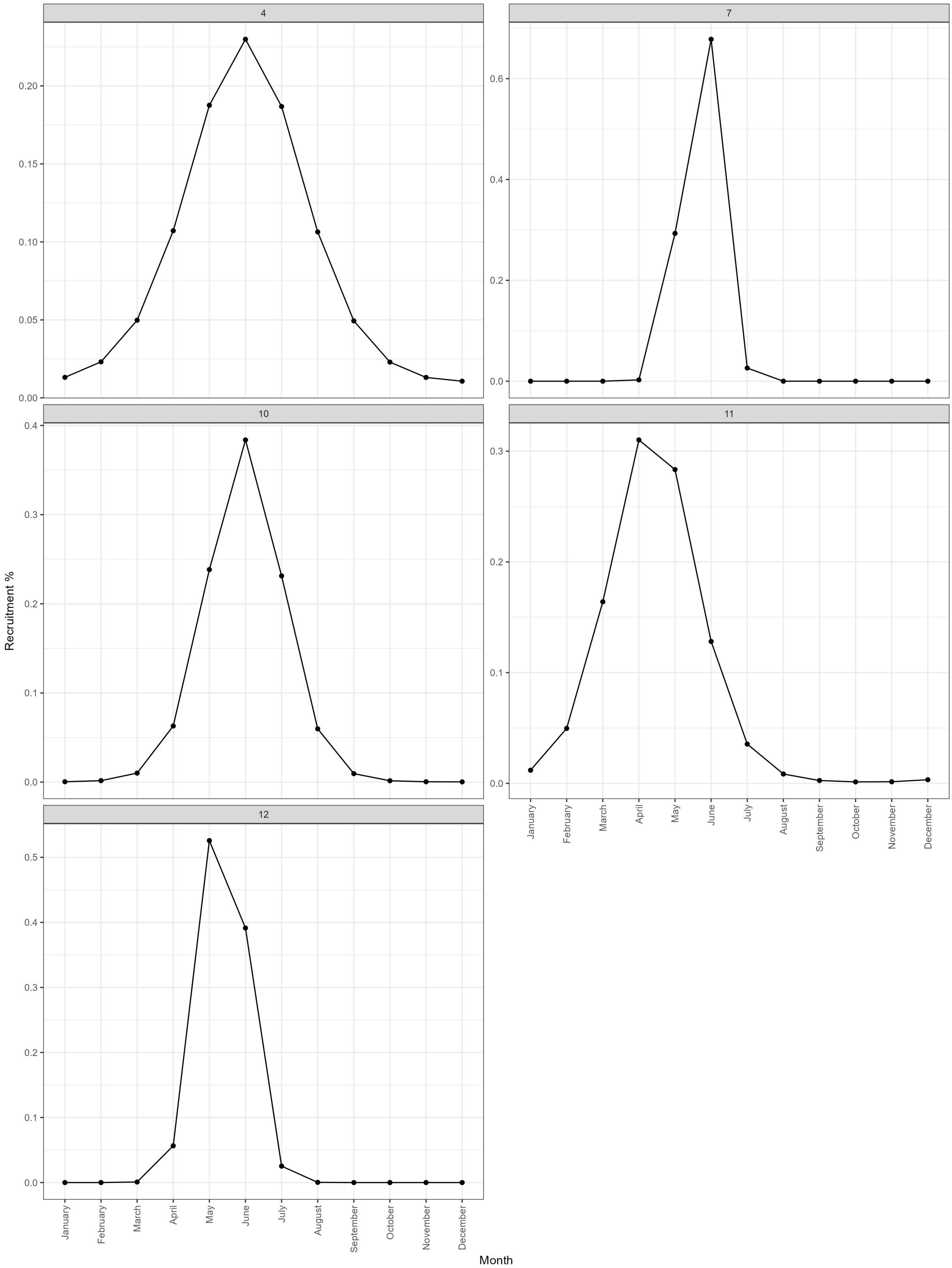


Figure B.97: Seasonal recruitment pattern plot for the mud bug model.

B.2.9 Seasonal catchability

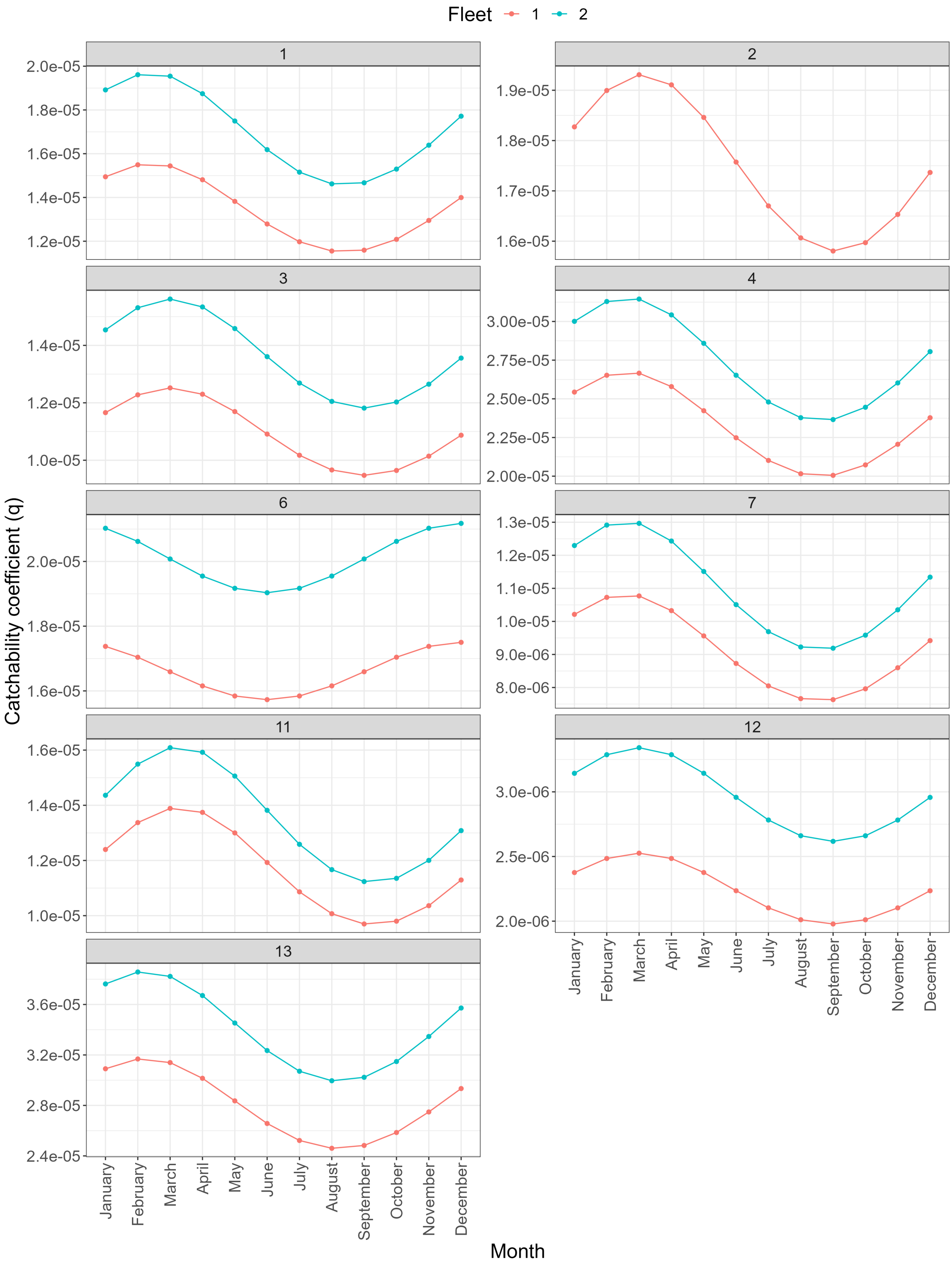


Figure B.98: Catchability plot for the sand bug model.

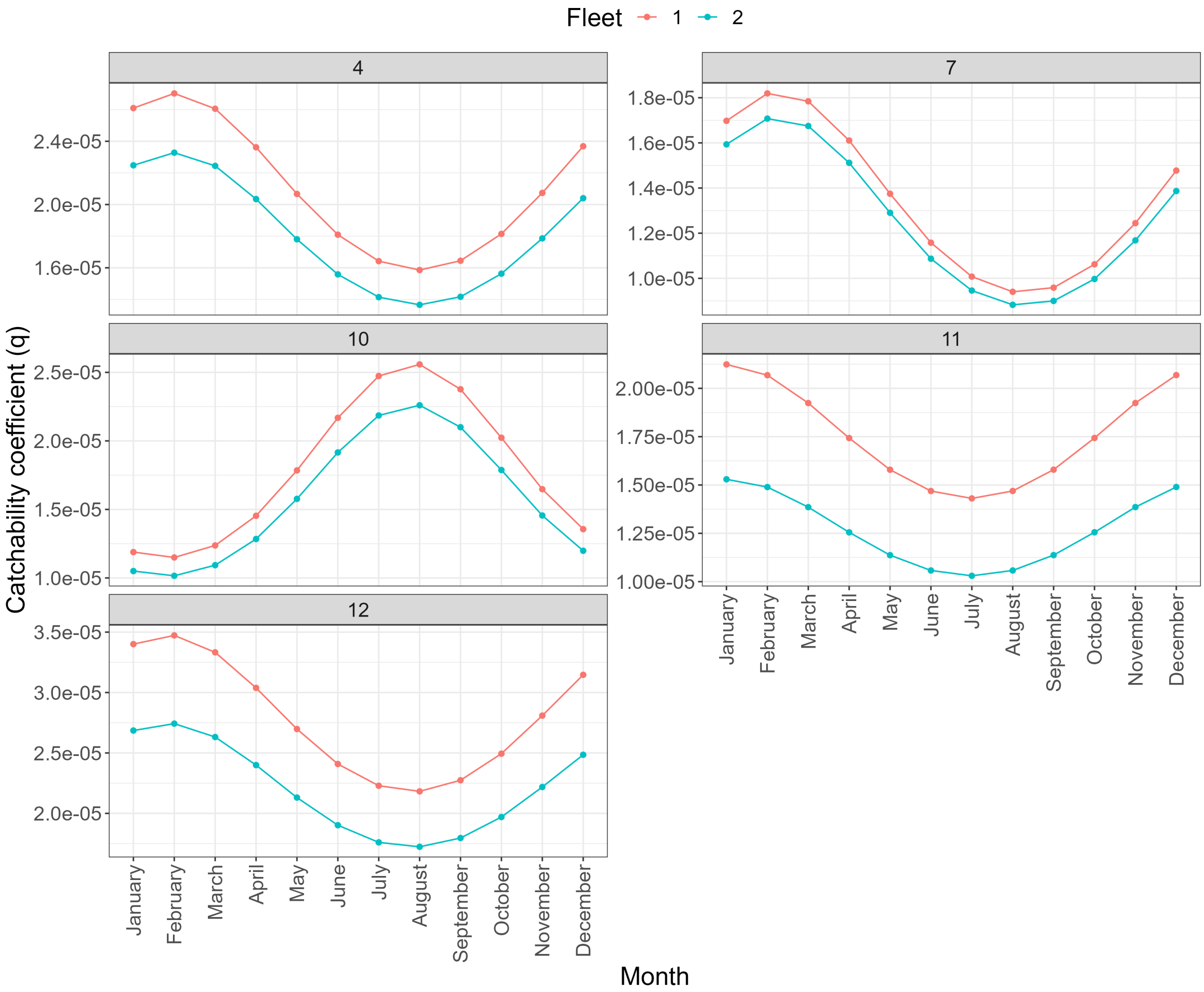


Figure B.99: Catchability plot for the mud bug model.

B.2.10 Fishing mortality

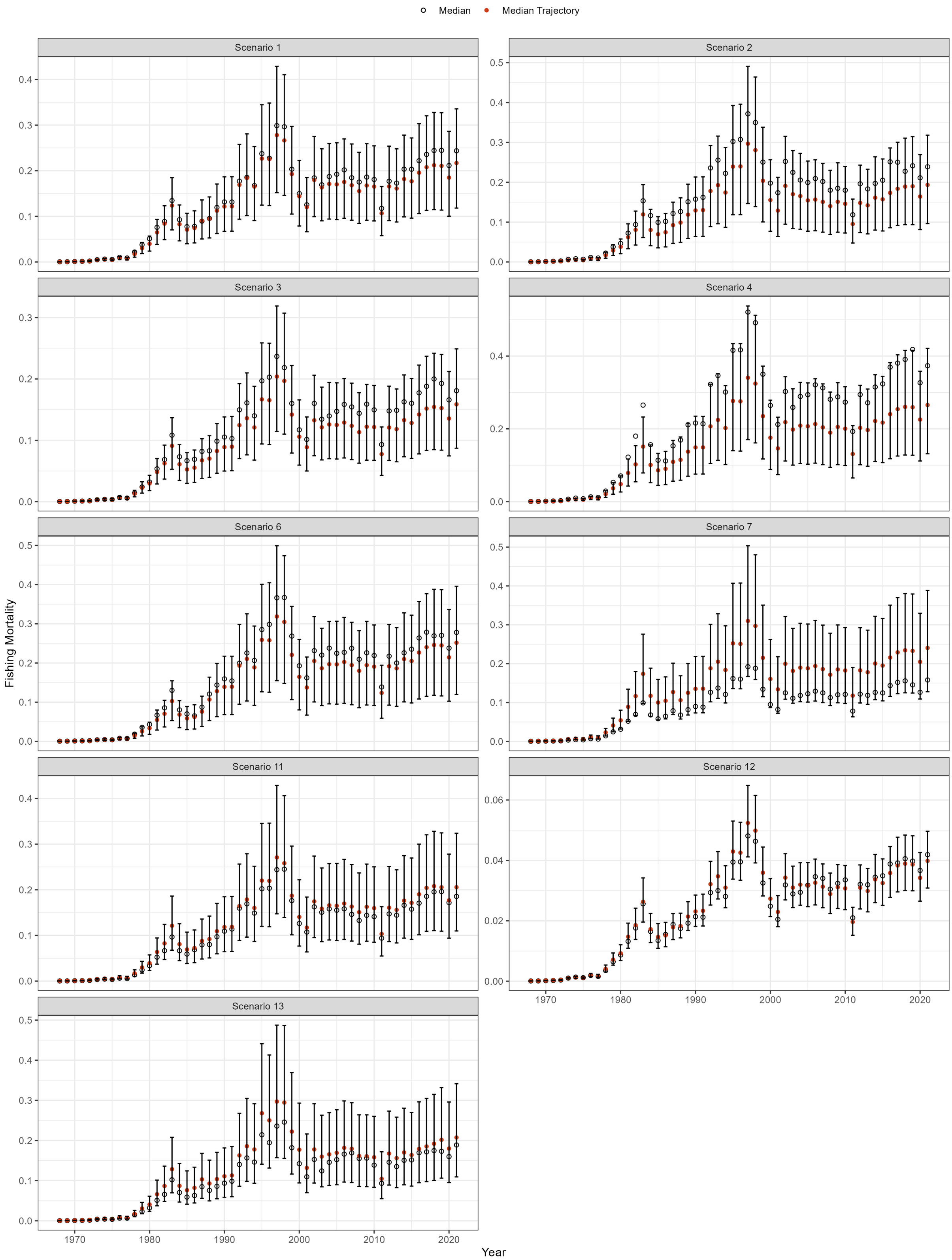


Figure B.100: Fishing mortality timeseries for the sand bug model

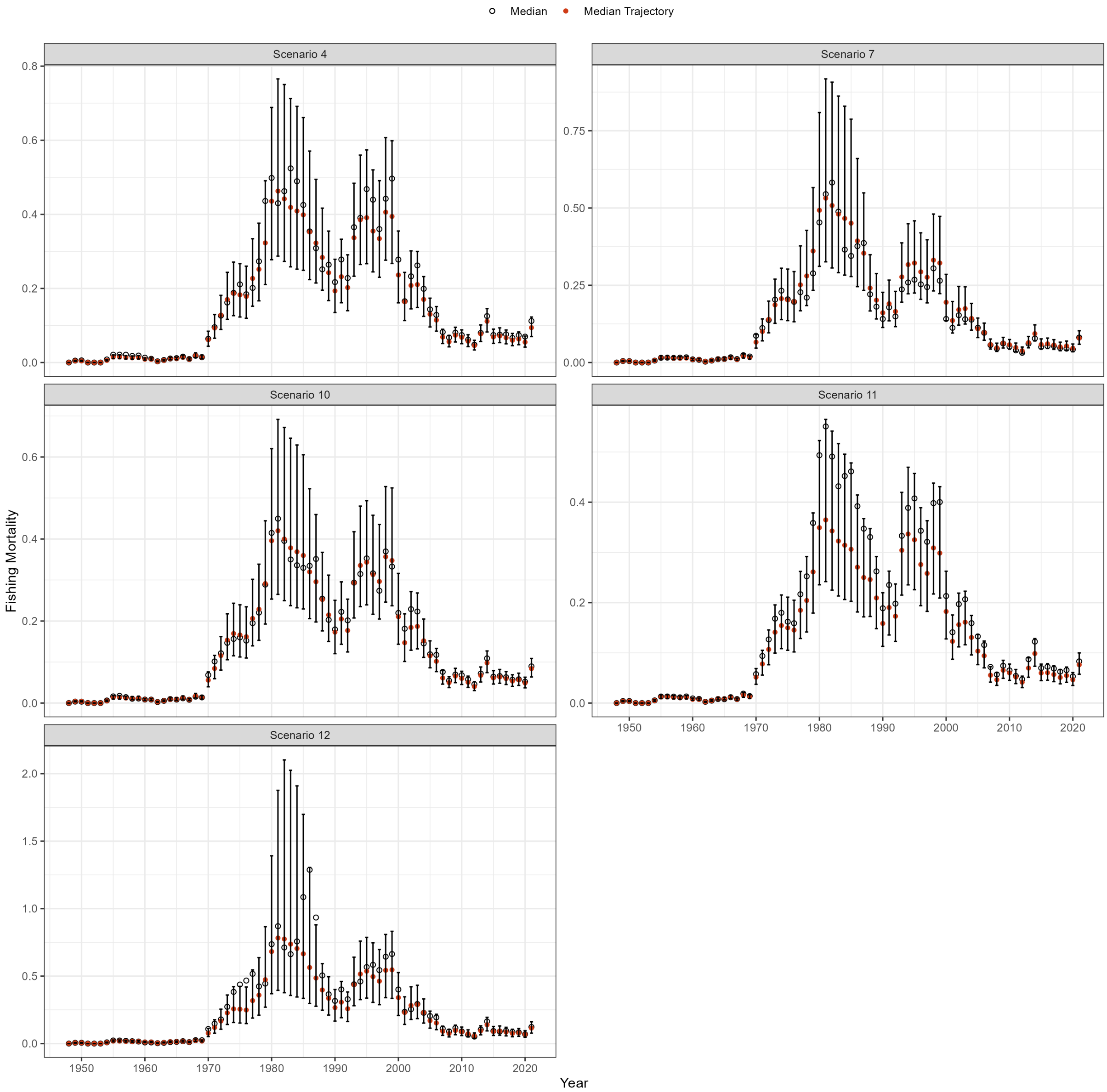


Figure B.101: Fishing mortality timeseries for the mud bug model

B.2.11 Phase plot

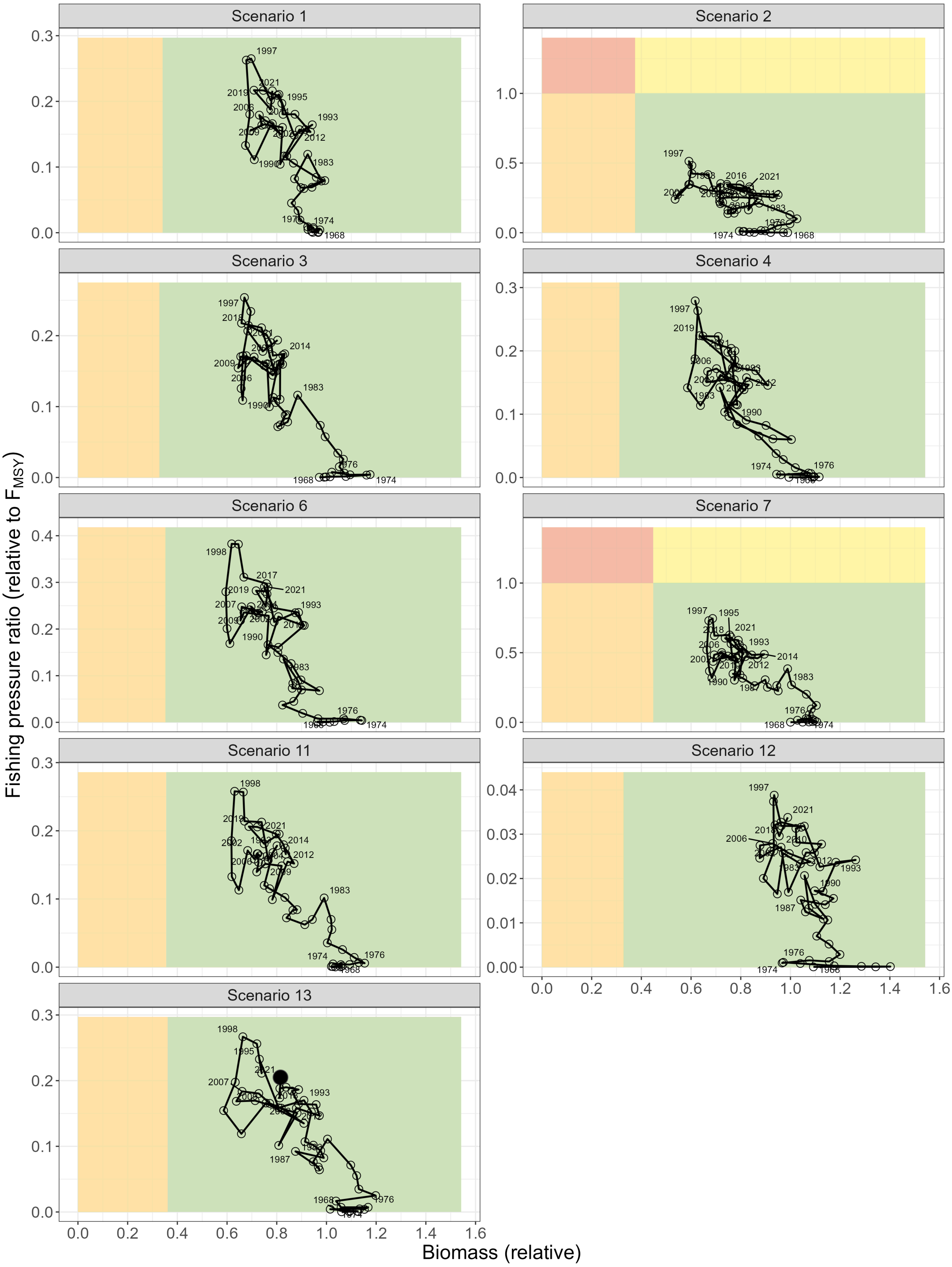


Figure B.102: Phase plot for the sand bug models – x-axis colour separation occurs at B_{MSY} and y-axis colour separation occurs at F_{MSY}

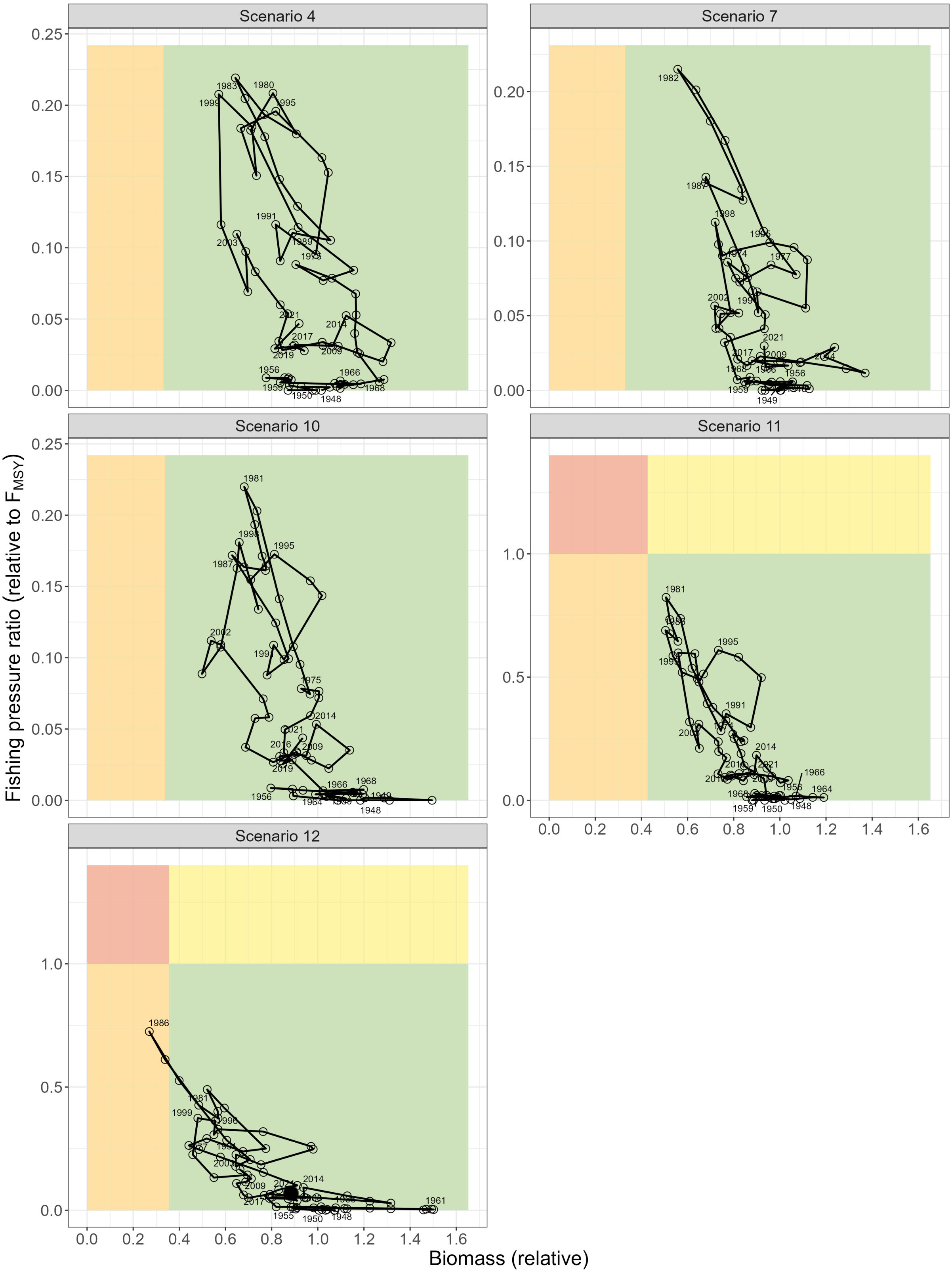


Figure B.103: Phase plot for the mud bug models – x-axis colour separation occurs at B_{MSY} and y-axis colour separation occurs at F_{MSY}

B.2.12 Yield curve

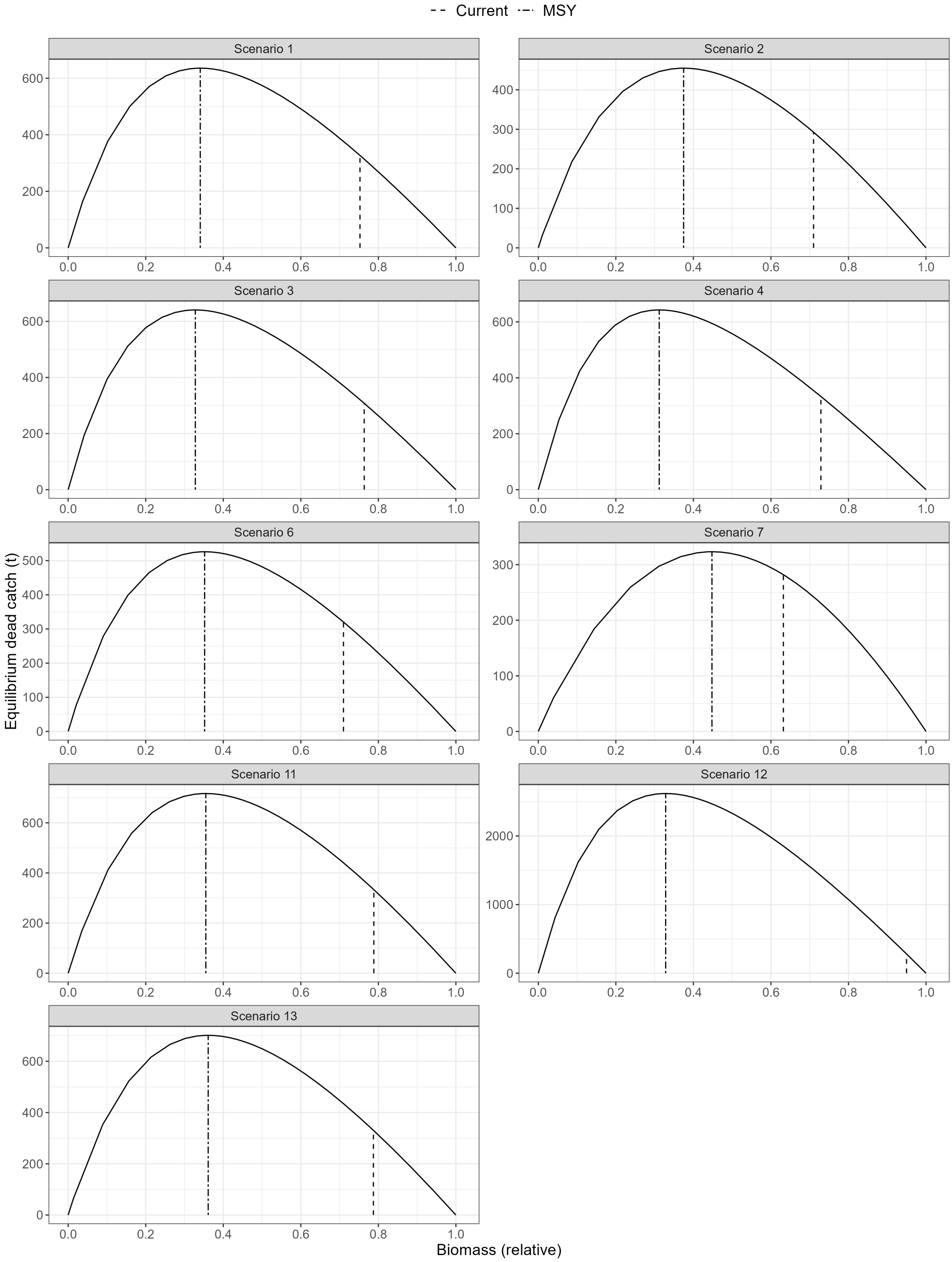


Figure B.104: Yield curve for the sand bug model.

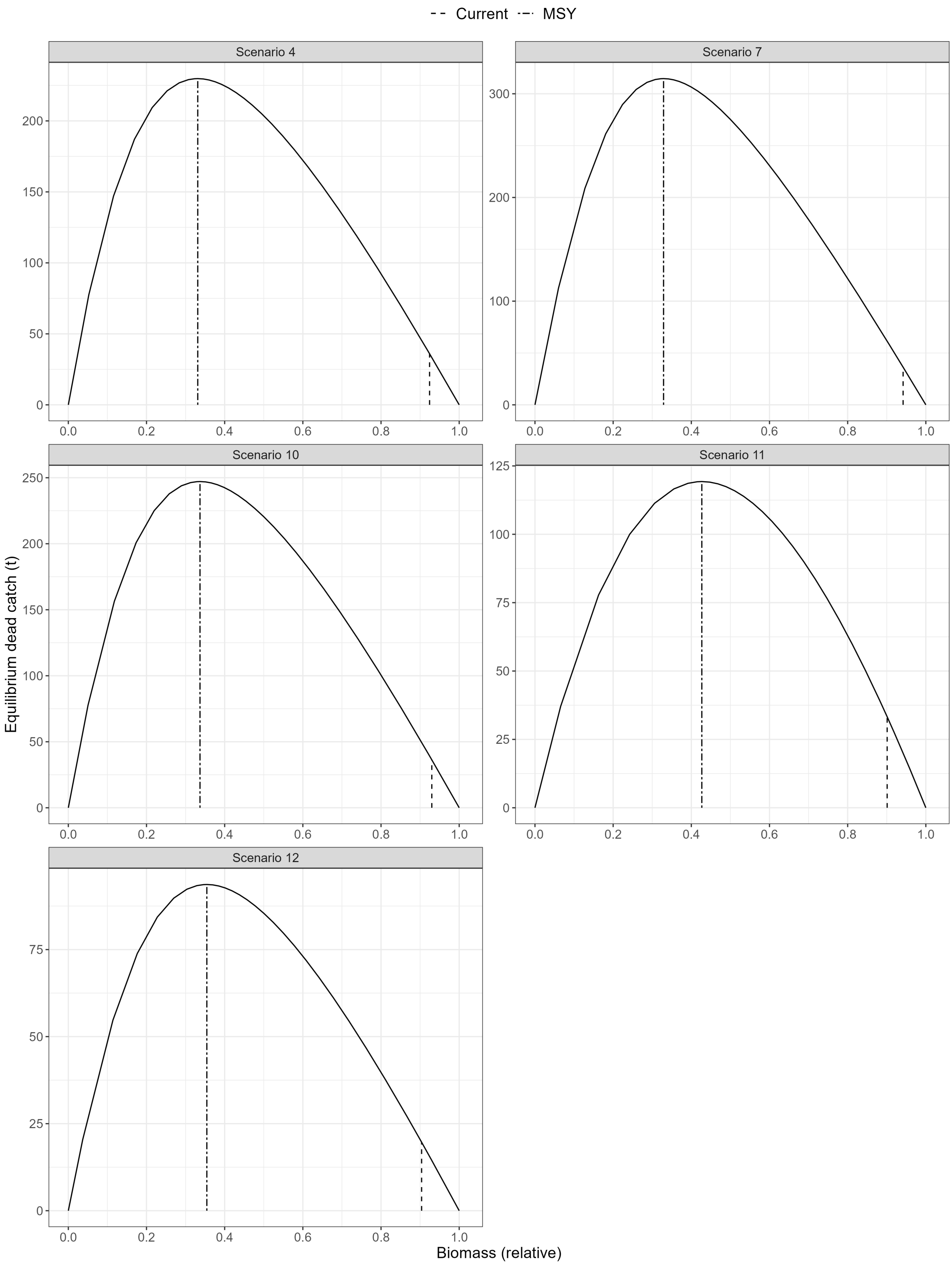


Figure B.105: Yield curve for the mud bug model.

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. Some of those topics are relevant to the Moreton Bay bugs assessment and are listed here.

- **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 three representatives on the project team (see Acknowledgements).
- **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. This was determined through literature research and project team discussions (Section 2.1.1, Appendix D).
- **Validity of the dynamic pool assumption (closed areas).** Various different techniques and methods were explored and discussed with the project team to address this. The validity of the dynamic pool assumption was explored through scenarios that split the catch rate temporally and through testing the impact of 'fraction fished' as an explanatory term in the standardisation.
- **Validity of the early data.** Extended discussion of historical catch reconstruction occurred during project team meetings (Appendix D). The final procedure for historical reconstruction of harvest is outlined in Section 2.3.
- **Handling uncertainty (more scenarios/priors).** Thirteen scenarios were run to investigate model uncertainty and sensitivity to fixed parameters and model assumptions. More detail can be found in Section 2.7.5.
- **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 2.7.3).
- **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 2.7.3).
- **Multi-species effects.** A targeting analysis was performed for bugs with its associated species. The results of this targeting analysis was entered into the catch rate standardisation as a model term (Section 2.4.3).

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. The southern boundary of the sand bug assessment was at 26° S whilst the southern boundary of the mud bug assessment was at 28° S (Figure 1.1).

The Gulf of Carpentaria was excluded from the current assessment as the oceanography between Cape York and Torres Strait likely presents a physical barrier preventing mixing between the east and west coasts of Queensland. For sand bugs, this barrier is bathymetry based, with a section of shallow water ($\leq$ 15 m) which is not preferred for sand bug habitation. For mud bugs, this barrier is sediment based, with a section of large grained sand which is not preferred for mud bug habitation.

- ***Meeting 3, Decision 1:*** *Grids in Torres Strait were removed for both species (minor larval sink with low demographic connectivity).*
- ***Meeting 3, Decision 1:*** *All X grids removed for both sand and mud bug (catches from the X grid columns are likely to be Balmain bug due to depth being greater than 80 m).*
- ***Meeting 3, Decision 1:*** *Exclude grids southward of W34 for sand bugs and exclude grids southward of W38 for mud bugs (sand bugs likely not found around Gold Coast and Sunshine Coast with high chance of Balmain bugs in deep water whilst mud bugs are likely not found south of Moreton bay).*

D.2 Historical catch

Several data sets of historical catch data were available to reconstruct the harvest of sand bugs back to 1968 and mud bug back to 1948. This included a mix of data from published literature, Htrawl voluntary commercial logbooks, compulsory commercial logbooks and vessel numbers.

- ***Meeting 1, Decision 1:*** *Using data from (Jones 1984), project team decided mud bug non-negligible harvest began in 1948.*
- ***Meeting 2, Decision 1:*** *Using data from (Jones 1984) and gear developments such as radar, project team decided sand bug non-negligible harvest began in 1968.*
- ***Meeting 3, Decision 3:*** *The preferred historical catch reconstruction for sand bugs should use the Htrawl catch-per-record trend with sensitivity testing for pattern and magnitude.*
- ***Meeting 3, Decision 3:*** *The preferred historical catch reconstruction for mud bugs should use the number of boats in the fishery with a linear decrease with sensitivity testing for pattern and magnitude.*

D.3 Catch rates

Extensive analysis of catch rates was performed and discussed with the project team. Catch rate formulation and diagnostics are presented in Sections 2.4 and Appendix B.2.

- ***Meeting 4, Decision 3:*** *Project team agreed for split catch rate time series for sand bugs aiming to capture changes in the re-zoning of the GBR through catchability. The continuous catch rate time series was used as a sensitivity scenario.*
- ***Meeting 4, Decision 4:*** *Project team agreed for split catch rate time series for mud bugs aiming to capture changes in the re-zoning of the GBR through catchability. The continuous catch rate time series was used as a sensitivity scenario.*

D.4 Model timestep

Two options for the time step used in the model were considered – annual or monthly. For species such as sand and mud bugs, models based on a monthly time step likely better reflect their biology. However, models based on an annual time step are more parsimonious, with a reduced number of parameters and simpler recruitment, spawning and catchability methods.

- ***Meeting 4, Decision 1:*** *Project team agreed for a monthly time step model based on the accurate capture of seasonal biological and fishing aspects of the sand bug stock. This, in turn, would bring in biological information and variability through the year that relates to the biology of the animal.*
- ***Meeting 4, Decision 2:*** *Project team agreed for a monthly time step model based on the accurate capture of seasonal biological and fishing aspects of the mud bug stock. This, in turn, would bring in biological information and variability through the year that relates to the biology of the animal.*

D.5 Natural mortality

The project team was presented three levels of natural mortality - 0.92 (literature value), 0.72 (low scenario) and 1.12 (high scenario) for sand bugs. For mud bugs, 1.26 (literature value), 1.06 (low scenario) and 1.46 (high scenario) were the three options presented.

- ***Meeting 4, Decision 5:*** *Project team agreed to keep the literature based natural mortality values of 0.92 and 1.26 for sand and mud bugs, respectively.*

Appendix E 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. (2006a), Courtney et al. (2014a), O'Neill et al. (2014), and Helidoniotis (2020c). 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.

E.1 Mathematical formulation

E.1.1 Population dynamics

The delay-difference model stages the population into recruits and spawners. The exploitable 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),

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

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

The exploitable biomass at time t depends on the exploitable 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 E.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 E.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.

E.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,

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

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 E.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,

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

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,

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

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 E.1 and E.2 are updated using the recruitment deviations described in Equation E.4

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

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

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

E.1.3 Spawning

The recruitment derived in Equation E.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:

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

where $i = \text{mod}(t, N_m) = t \mod N_m$. 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,

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

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

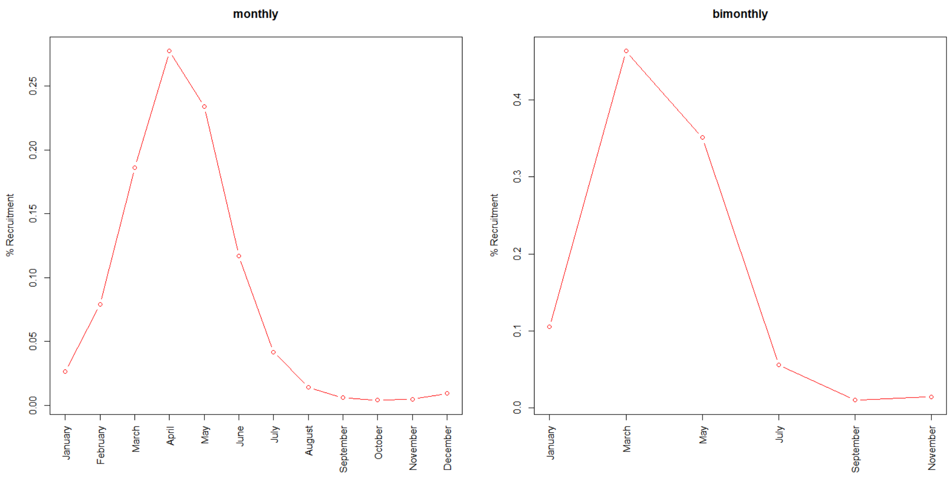


Figure E.1: Aggregation of a monthly recruitment pattern for a bi-monthly model

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

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

E.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

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

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 E.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.

E.1.5 Growth

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

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

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

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

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

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

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

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

Asymptotic weight from equation (E.16) is then

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

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:

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

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

E.1.6 Stock-recruitment parameters

Dichmont et al. (2003b) 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

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

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

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

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

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

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

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

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

Equilibrium spawning biomass is calculated as

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

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 E.3 are then

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

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).

E.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,

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

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:

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

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:

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

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

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

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

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

The predicted abundance index is therefore

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

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

E.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

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

The recruitment deviation log-likelihood in REDDUST is

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

The recruitment deviation log-likelihood in DDUST is

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

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

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

The recruitment penalty prevents the model from estimating an 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 E.2a the prior on the transformed parameter ξ is

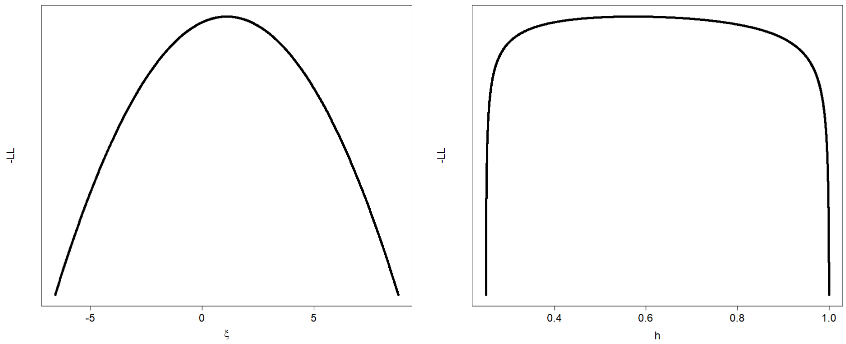
$$\xi \sim \text{Log-normal}(\mu_\xi = \log(3), \sigma_\xi^2 = 1). \tag{E.39}$$

Figure E.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

$$P_\xi = \frac{1}{2} \frac{(\xi - \mu_\xi)^2}{\sigma_\xi^2}, \tag{E.40}$$

$$P_\mu = \frac{1}{2} \frac{(\mu - \mu_\mu)^2}{\sigma_\mu^2}, \tag{E.41}$$

$$P_\kappa = \frac{1}{2} \frac{(\kappa - \mu_\kappa)^2}{\sigma_\kappa^2}. \tag{E.42}$$



(a) log-normal prior of transformed parameter ξ

(b) transformed prior of original parameter h

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

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

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

Appendix F Stock Synthesis modelling

F.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 are 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 molt 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 assessment aims to explore the use of an age-based analysis (Stock Synthesis) on two Moreton Bay bug populations (*Thenus australiensis* also known as the reef or sand bug, and *Thenus parindicus* also known as the mud bug), in Queensland Australia. In doing so, this assessment also aims to estimate the current biomass for the Queensland east coast sand and mud bug populations using both annual and monthly time step Stock Synthesis models.

F.2 Methods

Data and methods used for Stock Synthesis modelling were the same as those stated for DDUST modelling unless otherwise stated.

F.2.1 Data sources

Data used for Stock Synthesis modelling of sand and mud bugs is given in Table 2.1 in the main report. These data were used to form fishery-dependent commercial catch rates as an index of abundance, fishery independent survey index of abundance, length compositions, and annual retained catch. Data were summarised by source for both sand and mud bugs: survey and commercial. Further, sand bug commercial catch rate, retained catch, and length frequency data were split by gear type: commercial prawn and commercial scallop. Data sets were compiled by calendar year. Data are described in more detail in the following sections.

F.2.2 Regions

See Section 2.1.1 in main report.

F.2.3 Commercial

See Section 2.1.2 in main report.

F.2.4 Species splitting process

See Section 2.2 in main report.

F.2.5 Separation of fleets using trawl gear type

As Stock Synthesis can incorporate length-based data processes such as selectivity. Selectivity is important to model in the case of sand bugs as two different trawl gears are used in the fishery, prawn trawl and scallop trawl gear. Commercial logbook data were allocated as either prawn trawl or scallop trawl gear using the following process:

From 2006 onwards, commercial fishers were required to report which type of trawl gear was used on a particular night. Trawl fishers classify gear as red spot king prawn, eastern king prawn deep, eastern king prawn shallow, saucer scallop, Moreton Bay prawns, tiger/endeavour prawn, or banana prawn gear. For the purposes of modelling selectivity in Stock Synthesis, gear types were grouped into either prawn trawl (i.e, red spot king prawn, eastern king prawn deep, eastern king prawn shallow, Moreton Bay prawns, tiger/endeavour prawn, or banana prawn gear) or scallop trawl gear.

The trawl gear type used by each fisher could be inferred by the components of the catch. The major species within the catch were split into two groups, large species or prawns. Organisms such as endeavour prawns, tiger prawns, banana prawns, eastern king prawns, red spot king prawns, blue leg king prawns and prawn were allocated to the prawn group. Organisms such as scallop, sand bug, mud bug, cephlapods and crabs were allocated to the large organism group.

Given the large net mesh size of scallop trawl gear, when scallop trawl gear is used, prawns should generally account for a small proportion of the catch relative to large organisms. Given the small net mesh size of prawn trawl gear, when prawn trawl gear is used, prawns should generally account for a large proportion of the catch relative to large organisms. Subsequently, using records from 2006 onwards where fishers specified gear type in logbooks, the average weight in kilograms of prawns caught using scallop trawl gear was calculated to be 3.266 kg. Therefore, all records without a logbook reported gear type that had less than 3.266 kg of prawns were allocated as using scallop trawl gear. All records without a log book reported gear type that had greater than 3.266 kg of prawns were allocated as using prawn trawl gear. To validate this approach, records from 2006 onwards were also allocated to either scallop gear if the prawn component of the catch was less than 3.266 kg or allocated to prawn gear if the prawn component was greater than 3.266 kg to predict which gear was used. The predicted gear type used and logbook reported gear type used were cross referenced. Records from 2006 onwards were classified as either prawn trawl and scallop trawl gear with less than 6.5% error.

Prawn trawl gear and scallop trawl gear formed the basis for fleets in Stock Synthesis models.

F.2.6 Recreational, Indigenous and charter

See Section 2.2.1 in main report.

F.2.7 Retained catch estimates

See Section 2.3 in main report.

F.3 Standardised indices of abundance

See Section 2.4 in main report.

F.4 Model design

F.4.1 Population model

A population model with monthly time steps was fitted to the data to determine the number of sand and mud bugs 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. (2022).

Four fleet structures within Stock Synthesis were used depending on the species and scenario as outlined in Table F.1.

Table F.1: Fleet structure used in Stock Synthesis modelling

Species	Scenario	Number of Fleets	
Sand	1–12	6	survey pre-2004, survey post-2004, commercial prawn pre-2004, commercial prawn post-2004, commercial scallop pre-2004 and commercial scallop post-2004
	13–24	3	survey, commercial prawn and commercial scallop
Mud	1–12	3	survey, commercial pre-2004 and commercial post-2004
	13–24	2	survey and commercial

For sand bug models with continuous catch rate time series (Scenarios 13–24), three fleets were used (survey, commercial_prawn and commercial_scallop). For sand bug model with split catch rate time series (Scenarios 1–12), six fleets were used (survey_pre2004, survey_post24004, commercial_prawn_pre2004, commercial_prawn_post2004, commercial_scallop_pre2004 and commercial_scallop_post2004). For mud bug models with continuous catch rate time series (Scenarios 13–24), two fleets were used (survey and commercial). For mud bug models with split catch rate time series (Scenarios 1–12), three fleets were used (survey, commercial_pre2004 and commercial_post2004).

Both the sand and mud bug population models were run as a two-sex model.

F.4.2 Model assumptions

The main assumptions underlying the model are given below:

- The fishery began from an unfished state in 1968 for sand bugs and 1948 for mud bugs.
- Sand and mud bugs swim freely and mix rapidly within the bounds of each stock, so that the different fleets compete for the same sand and mud bugs rather than targeting different sub-populations.
- Genetic stocks along Queensland's east coast are reproductively isolated from one another.
- The proportion of mature sand and mud bugs depends on size and not age.
- The proportion of mature sand and mud bugs 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.

F.4.3 Model parameters

A variety of parameters were included in the model, with some of these fixed at specified values and others estimated. Uniform priors were not used unless stated. The phase, minimum, maximum and initial values for each parameter are given in Tables F.2, F.3, F.4 and F.5.

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

Recruitment was calculated once per year. For the annual time step Stock Synthesis model this recruitment was assigned to January. For the monthly time step Stock Synthesis model 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 symmetric beta 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 spawning biomass (Lee et al. 2012).

Stock Synthesis was configured to run a two-sex model for sand and mud bugs.

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 (CV_young) and old (CV_old) sand and mud bugs. Sex-specific growth curves were input to the model to capture sex-specific growth.

Natural mortality (NatM) was fixed in the model at 0.92 and 1.26 per year for sand and mud bugs (with sensitivity tests), respectively. Natural mortality rates were not modeled as sex-specific.

Logistic length-based selectivity parameters were estimated in the model without priors (Size_inflection, Size_95%width). For sand bug Stock Synthesis models with split catch rate time series (Scenarios 1–13), separate selectivity curves were estimated for the pre-2004 and post-2004 prawn trawl fleets.

Recruitment deviations (1968–2021 for bugs and 1948–2021 for mud bugs) 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.

Table F.2: Summary of parameter settings from the annual Stock Synthesis sand bug population model

Parameter	Phase	Min	Max	Initial value
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1968)	1	3	30	18
Beverton-Holt steepness parameter	3	0.2	1	0.4
Additional esitmated error for survey post2004 fleet index	8	0	1	0
Additional esitmated error for commercial prawn pre2004 fleet catch rate	8	0	1	0
Additional esitmated error for commercial prawn post2004 fleet catch rate	8	0	1	0
Commercial survey pre2004 fleet selectivity inflection (cm)	2	0	8	5
Commercial survey pre2004 fleet selectivity width (cm)	3	0	3	0.8
Commercial survey post2004 fleet selectivity inflection (cm)	2	0	8	5
Commercial survey post2004 fleet selectivity width (cm)	3	0	3	0.8

Table F.3: Summary of parameter settings from the annual Stock Synthesis mud bug population model

Parameter	Phase	Min	Max	Initial value
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1968)	1	3	30	15
Beverton-Holt steepness parameter	3	0.2	1	0.4
Additional esitmated error for commercial pre2004 fleet catch rate	8	0	1	0
Additional esitmated error for commercial post2004 fleet catch rate	8	0	1	0
Commercial survey pre2004 fleet selectivity inflection (cm)	2	0	9	3.5
Commercial survey post2004 fleet selectivity width (cm)	3	0	3	1

Table F.4: Summary of parameter settings from the monthly Stock Synthesis sand bug population model

Parameter	Phase	Min	Max	Initial value
Recruitment distribution parameter for January	5	-100	100	0
Recruitment distribution parameter for February	5	-100	100	0
Recruitment distribution parameter for March	5	-100	100	0
Recruitment distribution parameter for April	5	-100	100	0
Recruitment distribution parameter for May	5	-100	100	0
Recruitment distribution parameter for June	5	-100	100	0
Recruitment distribution parameter for July	5	-100	100	0
Recruitment distribution parameter for August	5	-100	100	0
Recruitment distribution parameter for September	5	-100	100	0
Recruitment distribution parameter for October	5	-100	100	0
Recruitment distribution parameter for November	5	-100	100	0
Recruitment distribution parameter for December	5	-100	100	0
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1968)	1	3	30	18
Beverton-Holt steepness parameter	3	0.2	1	0.4
Additional esitmated error for survey post2004 fleet index	8	0	1	0
Additional esitmated error for commercial prawn pre2004 fleet catch rate	8	0	1	0
Additional esitmated error for commercial prawn post2004 fleet catch rate	8	0	1	0
Commercial survey pre2004 fleet selectivity inflection (cm)	2	0	8	5
Commercial survey pre2004 fleet selectivity width (cm)	3	0	3	0.8
Commercial survey post2004 fleet selectivity inflection (cm)	2	0	8	5
Commercial survey post2004 fleet selectivity width (cm)	3	0	3	0.8

Table F.5: Summary of parameter settings from the monthly Stock Synthesis mud bug population model

Parameter	Phase	Min	Max	Initial value
Recruitment distribution parameter for January	5	-100	100	0
Recruitment distribution parameter for February	5	-100	100	0
Recruitment distribution parameter for March	5	-100	100	0
Recruitment distribution parameter for April	5	-100	100	0
Recruitment distribution parameter for May	5	-100	100	0
Recruitment distribution parameter for June	5	-100	100	0
Recruitment distribution parameter for July	5	-100	100	0
Recruitment distribution parameter for August	5	-100	100	0
Recruitment distribution parameter for September	5	-100	100	0
Recruitment distribution parameter for October	5	-100	100	0
Recruitment distribution parameter for November	5	-100	100	0
Recruitment distribution parameter for December	5	-100	100	0
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1968)	1	3	30	15
Beverton-Holt steepness parameter	3	0.2	1	0.4
Additional esitmated error for commercial pre2004 fleet catch rate	8	0	1	0
Additional esitmated error for commercial post2004 fleet catch rate	8	0	1	0
Commercial survey pre2004 fleet selectivity inflection (cm)	2	0	9	3.5
Commercial survey post2004 fleet selectivity width (cm)	3	0	3	1

F.4.4 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).

F.4.5 Sensitivity tests

The following 24 scenarios were tested for each of the annual and monthly sand bug and mud bug models (Table F.6). For natural mortality, medium levels were those reported in the literature from Courtney (1997) at 0.92 and 1.26 (averaged across males and females) per year for sand and mud bugs, respectively. Scenarios of low natural mortality are −0.2 whilst high natural mortality is +0.2 of the medium (literature) values.

See Section 2.7.5 for more detail regarding the sensitivity tests of split or continuous catch rates, harvest, natural mortality and data used in catch rate standardisation.

Table F.6: Sensitivity scenarios tested across annual and monthly sand and and mud bug models in Stock Synhtesis

Scenario	Rezoning	Retained catch	Natural Mortality	Catch rate data
1	Split	100%	Medium	All non-zero
2	Split	100%	Low	All non-zero
3	Split	100%	High	All non-zero
4	Split	pattern	Medium	All non-zero
5	Split	pattern	Low	All non-zero
6	Split	pattern	High	All non-zero
7	Split	75%	Medium	All non-zero
8	Split	75%	Low	All non-zero
9	Split	75%	High	All non-zero
10	Split	125%	Medium	All non-zero
11	Split	125%	Low	All non-zero
12	Split	125%	High	All non-zero
13	Continuous	100%	Medium	All non-zero
14	Continuous	100%	Low	All non-zero
15	Continuous	100%	High	All non-zero
16	Continuous	pattern	Medium	All non-zero
17	Continuous	pattern	Low	All non-zero
18	Continuous	pattern	High	All non-zero
19	Continuous	75%	Medium	All non-zero
20	Continuous	75%	Low	All non-zero
21	Continuous	75%	High	All non-zero
22	Continuous	125%	Medium	All non-zero
23	Continuous	125%	Low	All non-zero
24	Continuous	125%	High	All non-zero
25	Split	100%	Medium	Target data only

F.5 Results

F.5.1 Model inputs

F.5.1.1 Data availability

An illustration of data presence as data inputs for the Stock Synthesis models are shown in Figure F.1 for sand bugs and Figure F.2 for mud bugs. The data presence corresponds to the six fleets for sand bugs and three fleets for mud bugs as defined for the Stock Synthesis model. These illustrations represent Scenario 1 Stock Synthesis models for sand and mud bugs.

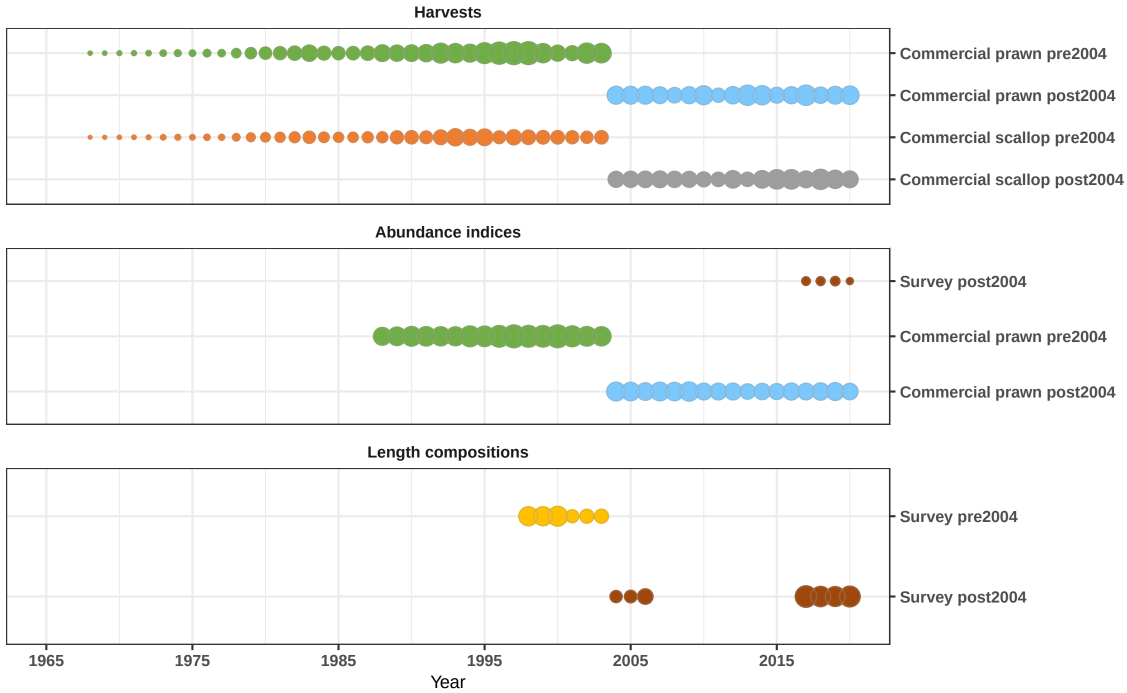


Figure F.1: Data presence by calendar year for each category of data type and Stock Synthesis fleet for the sand bug east coast stock

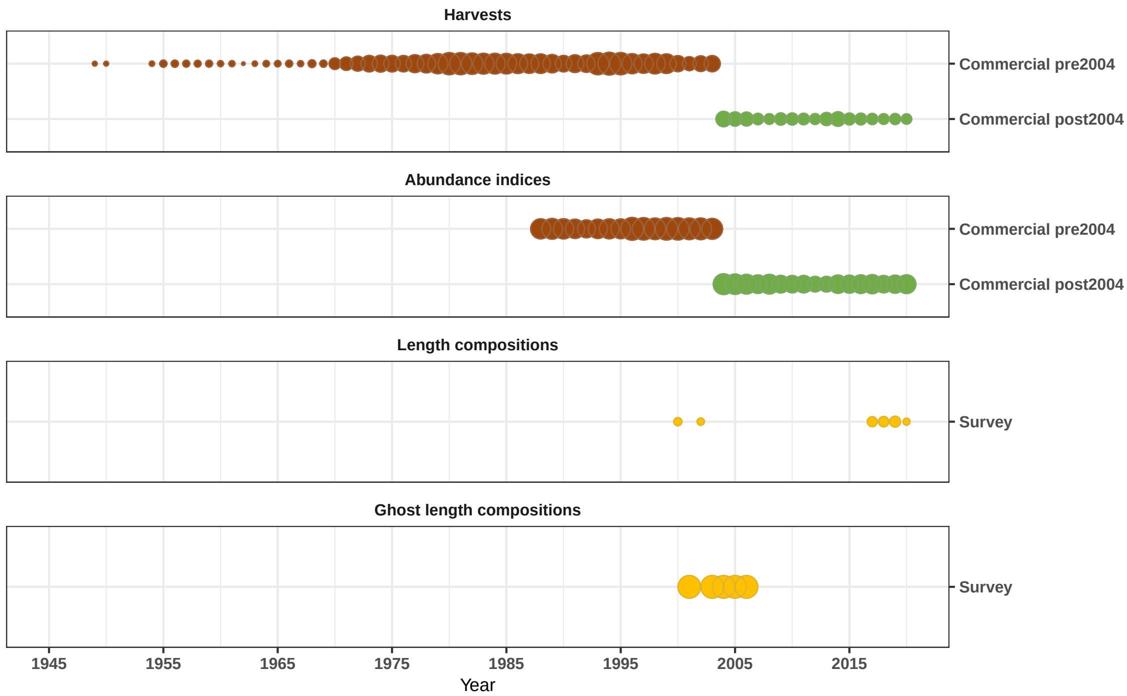


Figure F.2: Data presence by calendar year for each category of data type and Stock Synthesis fleet for the mud bug east coast stock

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). This assessment for sand bugs involves six fleets:

- survey_pre2004 for fishery independent data prior to 2004,
- survey_post24004 for fishery independent data post 2004,
- commercial_prawn_pre2004 for fishers using prawn trawl gear prior to 2004 ,
- commercial_prawn_post2004 for fishers using prawn trawl gear post 2004 ,
- commercial_scallop_pre2004 for fishers using scallop trawl gear prior to 2004, and
- commercial_scallop_post2004 for fishers using scallop trawl gear post 2004.

This assessment for mud bugs involves three fleets:

- survey for fishery independent data (limited data prior to 2004 so all data were grouped),
- commercial_pre2004 for all commercial data prior to 2004, and
- commercial_post2004 for all commercial data post 2004.

Figures F.1 and F.2 show data presence by year for each fleet, where circle area is relative within a data type. Circle areas are proportional to total harvest for harvests; to precision for indices; and to total sample size for compositions. Note that since the circles are scaled relative to maximums within each data type, the scaling within separate plots should not be compared.

F.5.1.2 Retained catch estimates

Retained catch estimates were the same as those used in Section 3.1.2 aside from the splitting of retained catch by fleet. For sand bugs, commercial retained harvest were split by gear type (i.e., prawn trawl fleet and scallop trawl fleet). Additionally, if split standardised catch rates were used, harvests were split to pre-2004 and post-2004 (Figure F.3).

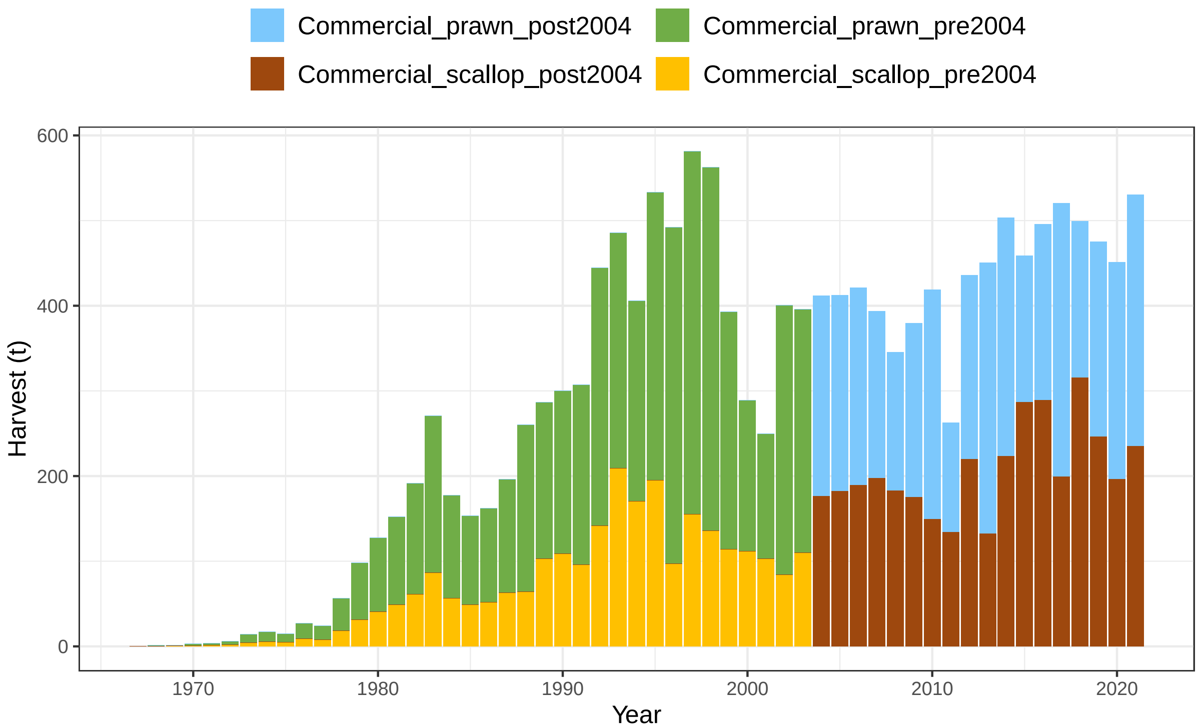


Figure F.3: Annual estimated harvest (retained catch) for sand bugs between 1968 and 2021

If split standardised catch rates were used for mud bugs, harvests were split to pre-2004 and post-2004 (Figure F.4).

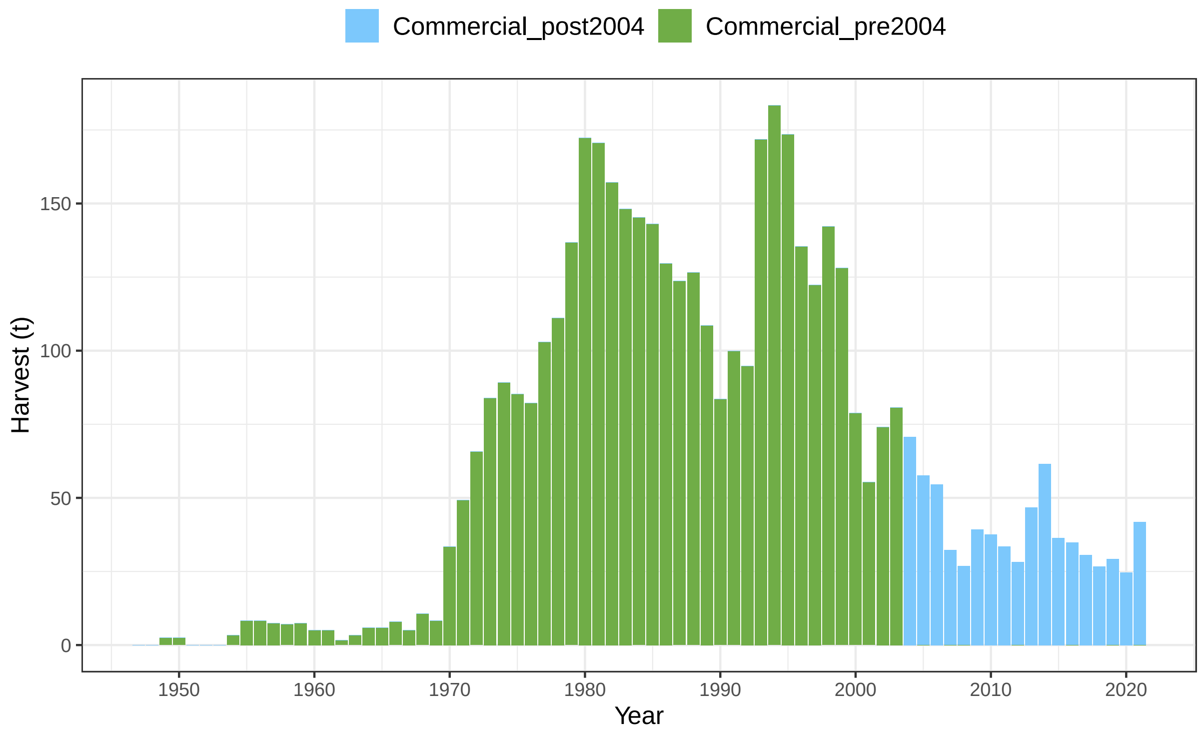


Figure F.4: Annual estimated harvest (retained catch) for mud bugs between 1948 and 2021

F.5.1.3 Standardised indices of abundance

Standardised catch rates were the same as those used in Section 2.4 unless otherwise stated.

Sand bug annual standardised catch rates for the commercial prawn fleet and survey fleet are presented in Figure F.5 and Figure F.6. Mud bug annual standardised survey catch rates for the commercial fleet are presented in Figure F.7. Sand bug monthly standardised catch rates for the commercial prawn fleet are presented in Figure F.8. Mud bug monthly standardised catch rates for the commercial fleet are presented in Figure F.9.

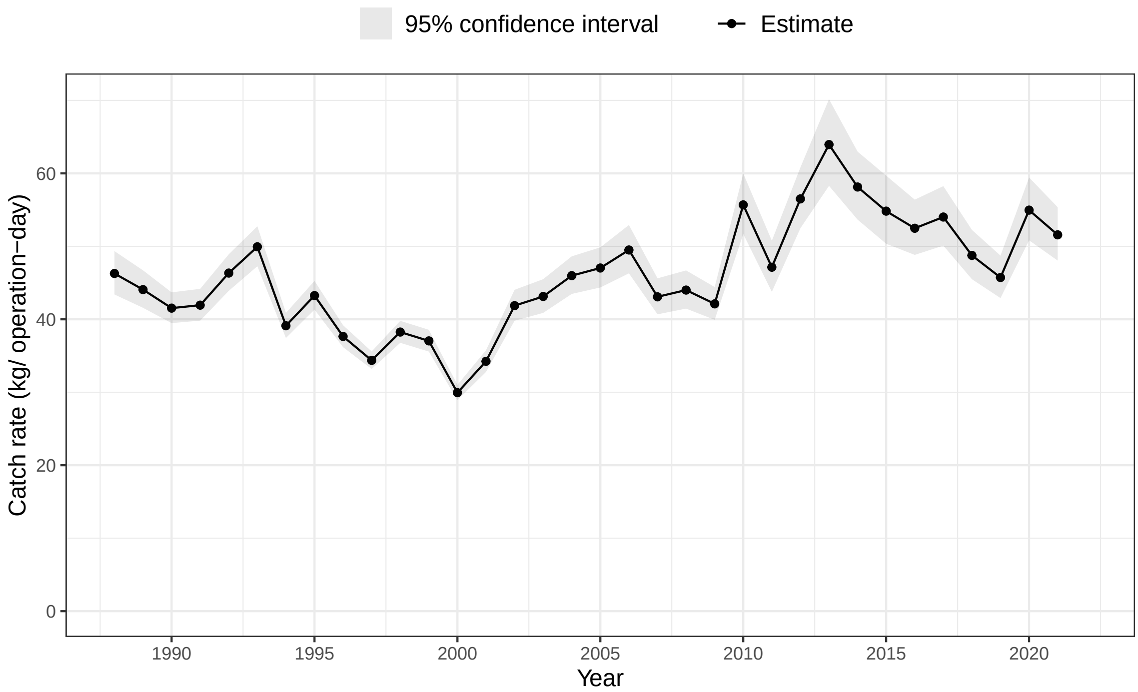


Figure F.5: Annual standardised catch rates for commercially caught sand bugs between the years of 1988 and 2021 for the east coast stock

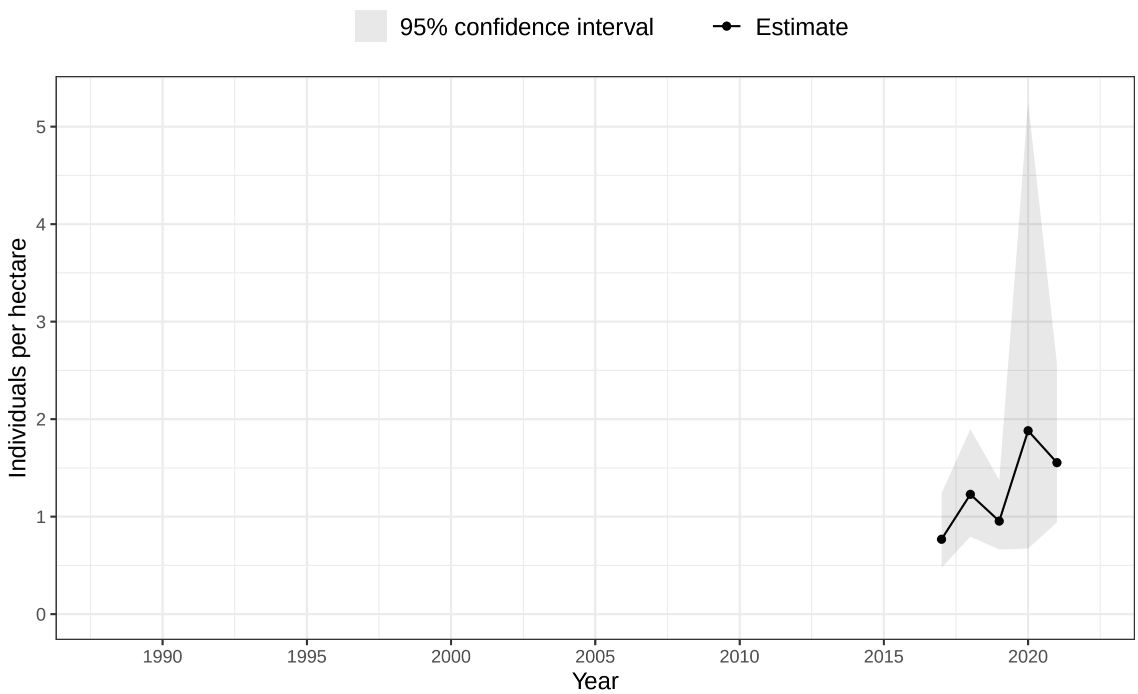


Figure F.6: Annual standardised index of sand bug abundance from fishery independent surveys (2017–2021)

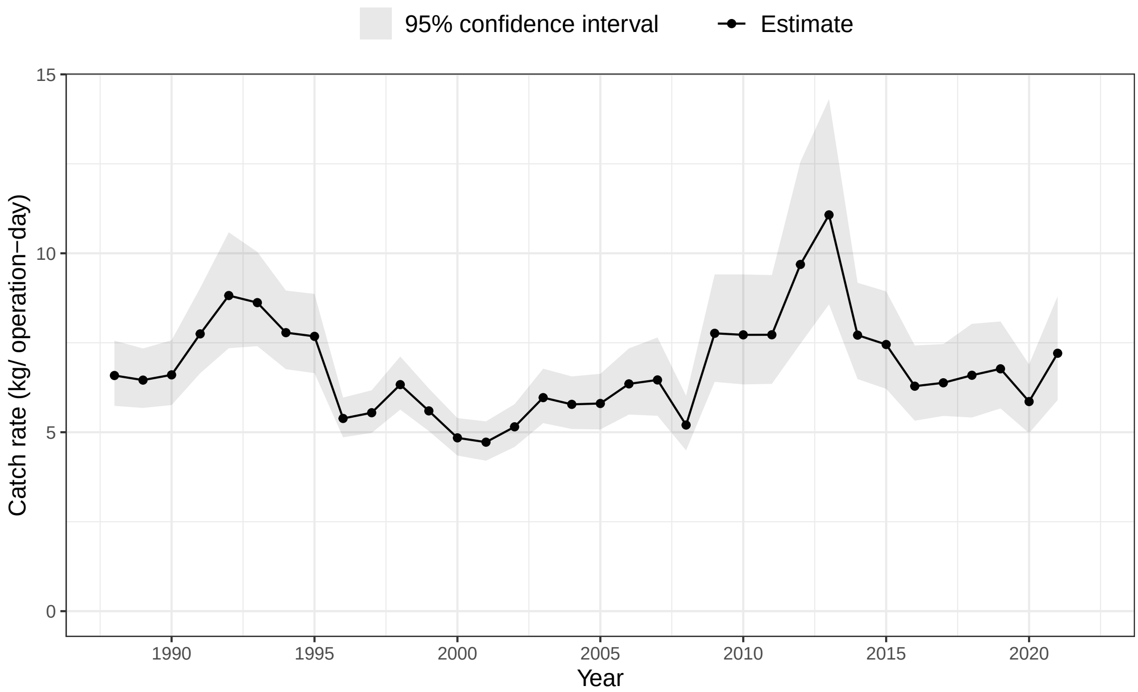


Figure F.7: Annual standardised catch rates for commercially caught mud bugs between the years of 1988 and 2021 for the east coast stock

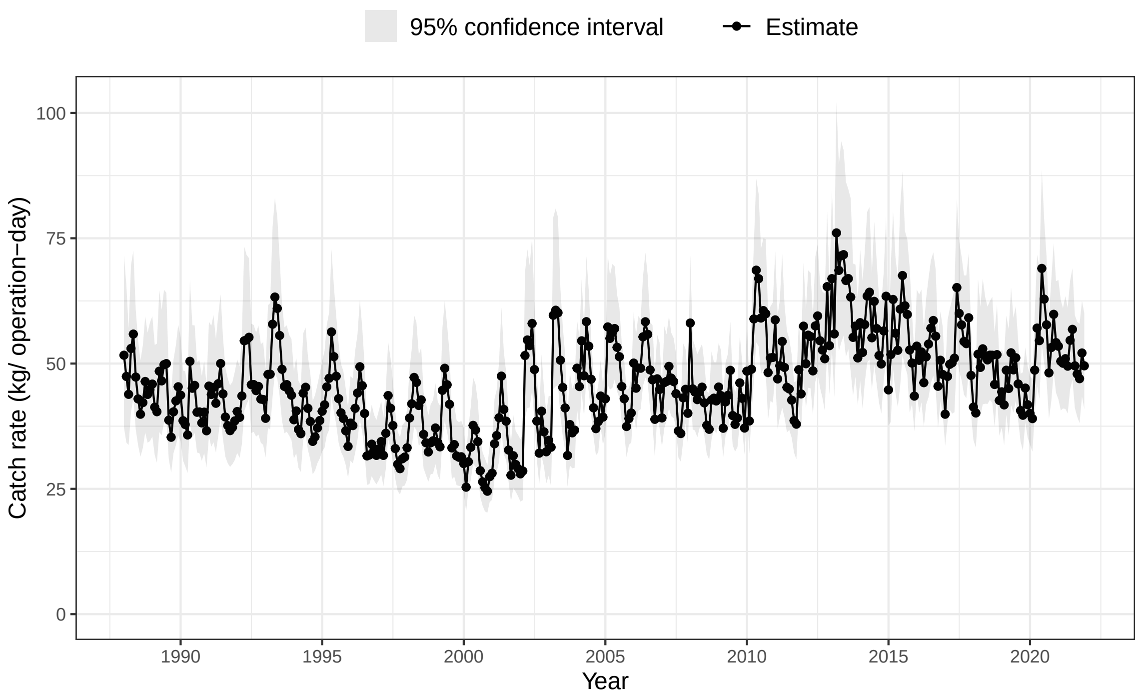


Figure F.8: Monthly standardised catch rates for commercially caught sand bugs between the years of 1988 and 2021 for the east coast stock

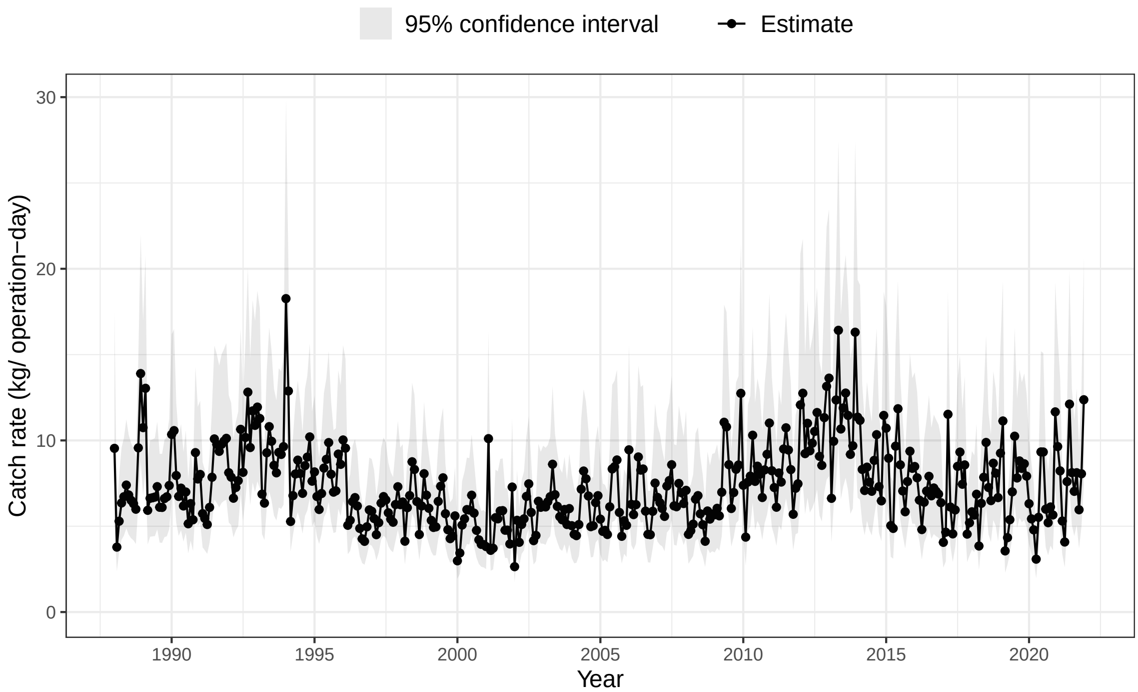


Figure F.9: Monthly standardised catch rates for commercially caught mud bugs between the years of 1988 and 2021 for the east coast stock

F.5.1.4 Length composition

Fishery independent sand bug length compositions were input to the Stock Synthesis model for the survey pre-2004 and survey post-2004 fleets (Figure F.10). Fishery independent mud bug length compositions were input to the Stock Synthesis model for the survey fleet (Figure F.11). Additionally, a second source of fishery independent length frequency data were input to the survey post-2004 fleet for sand bugs (Figure F.12) and survey fleet for mud bugs (Figure F.13). Further length frequency data was available from Jones (1988) however (see Figures F.14 and F.15), a year could not be assigned to the data and was therefore excluded from length frequency modelling.

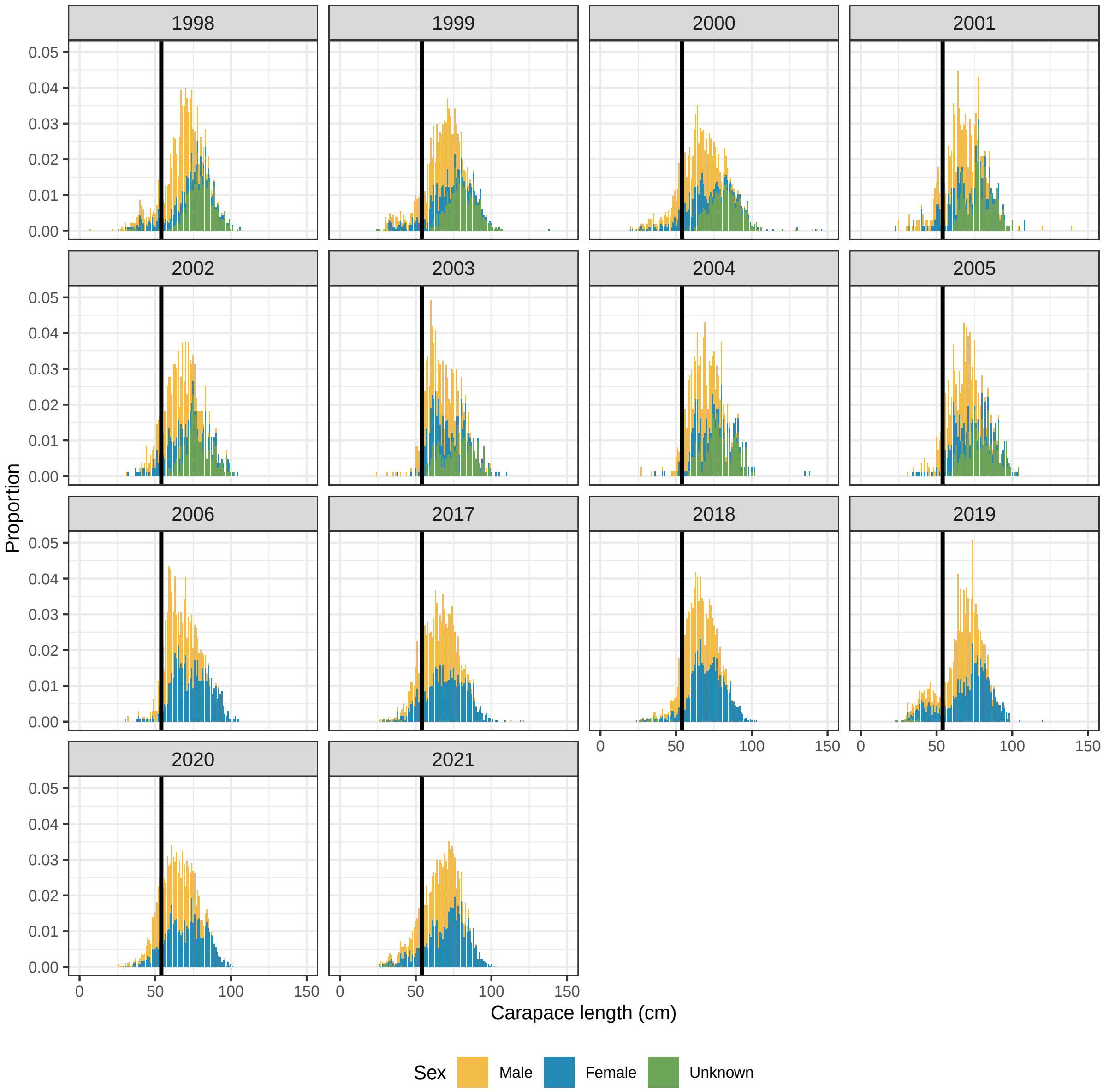


Figure F.10: Annual length compositions of male, female and unknown sex sand bugs for the survey fleet (FM)

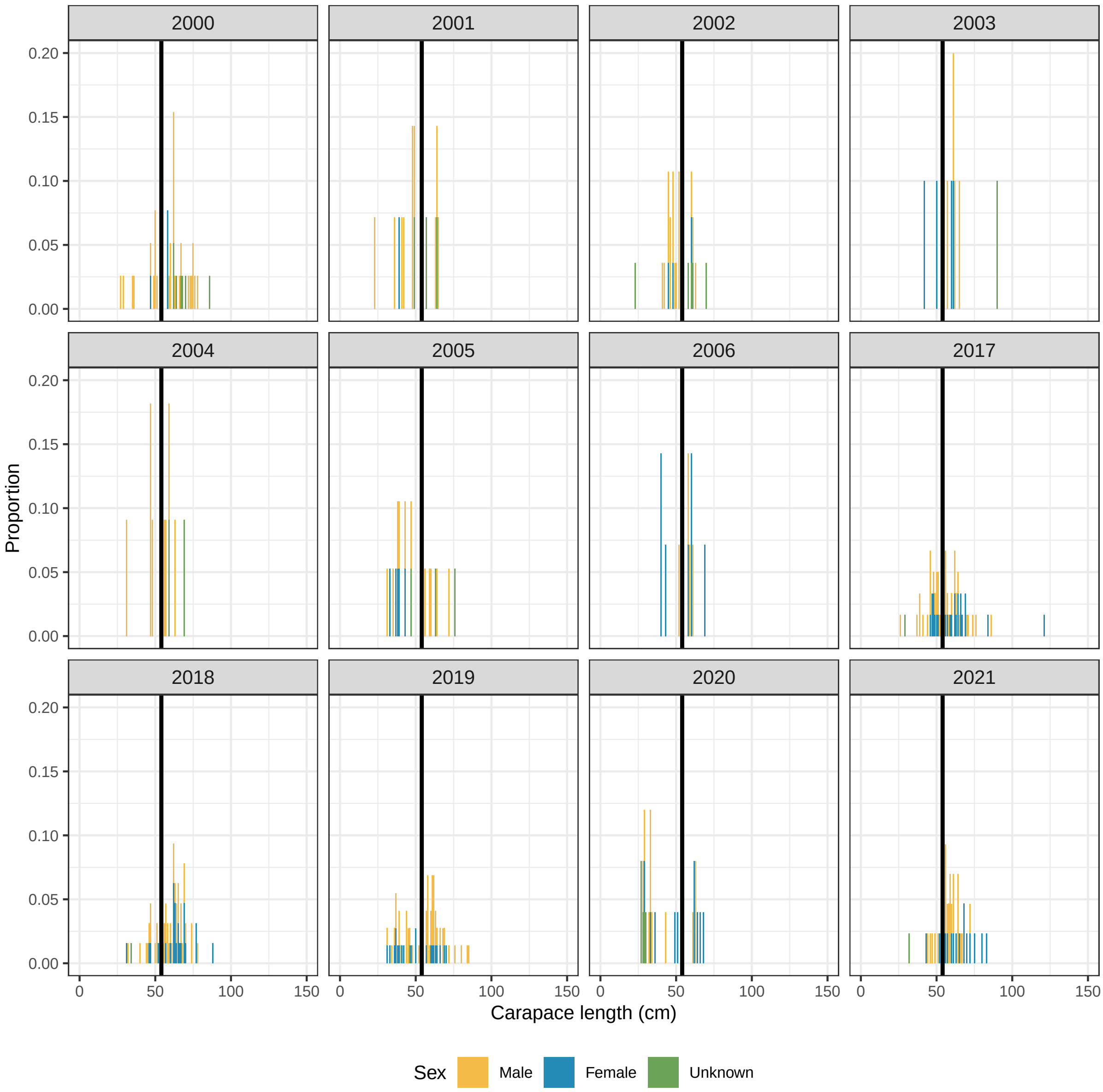


Figure F.11: Annual length compositions of male, female and unknown sex mud bugs for the survey fleet (FM)

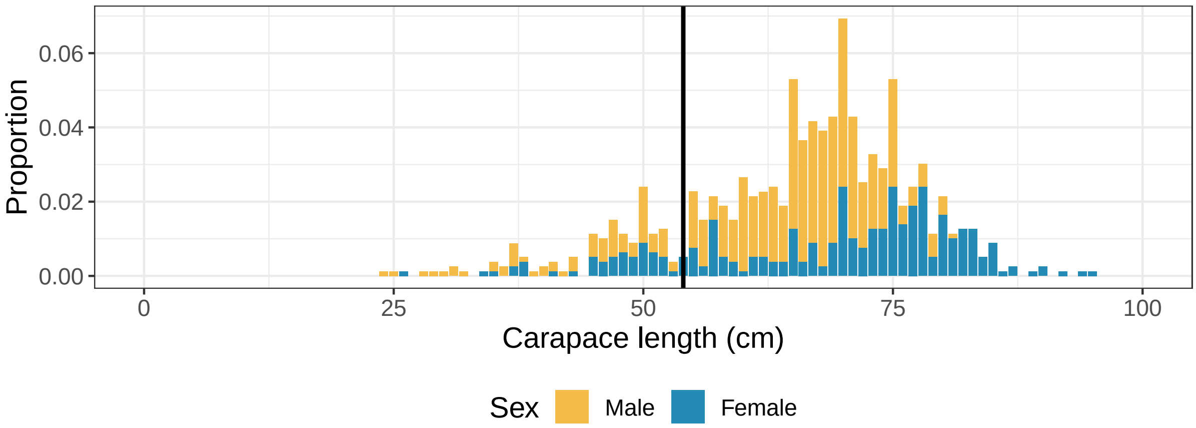


Figure F.12: Annual length compositions of male and female sand bugs for the survey fleet (FRDC)

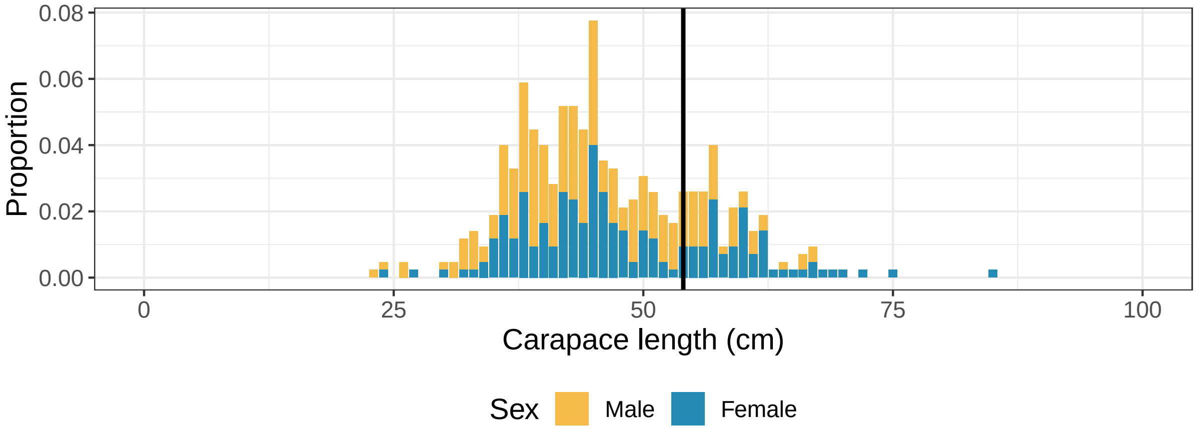


Figure F.13: Annual length compositions of male and female mud bugs for the survey fleet (FRDC)

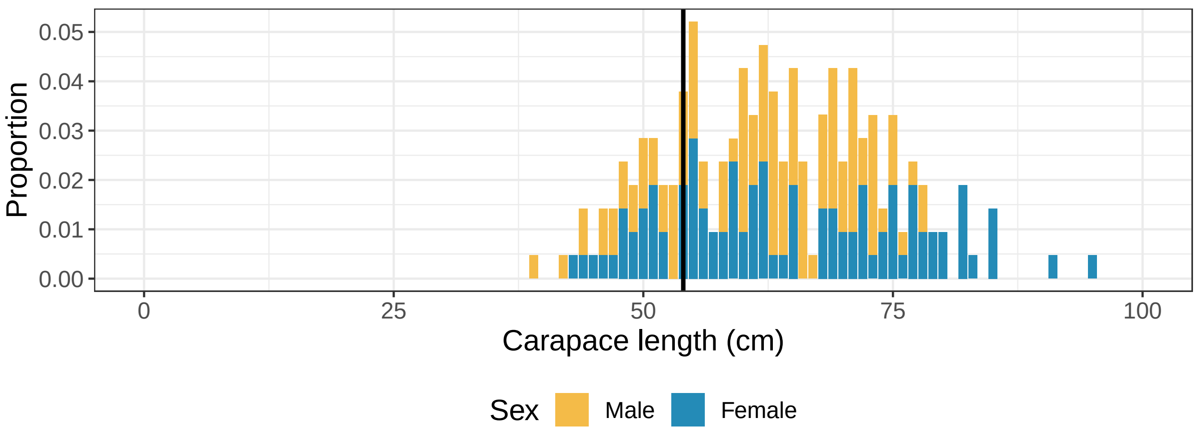


Figure F.14: Length compositions of male and female sand bugs from Jones (1988)

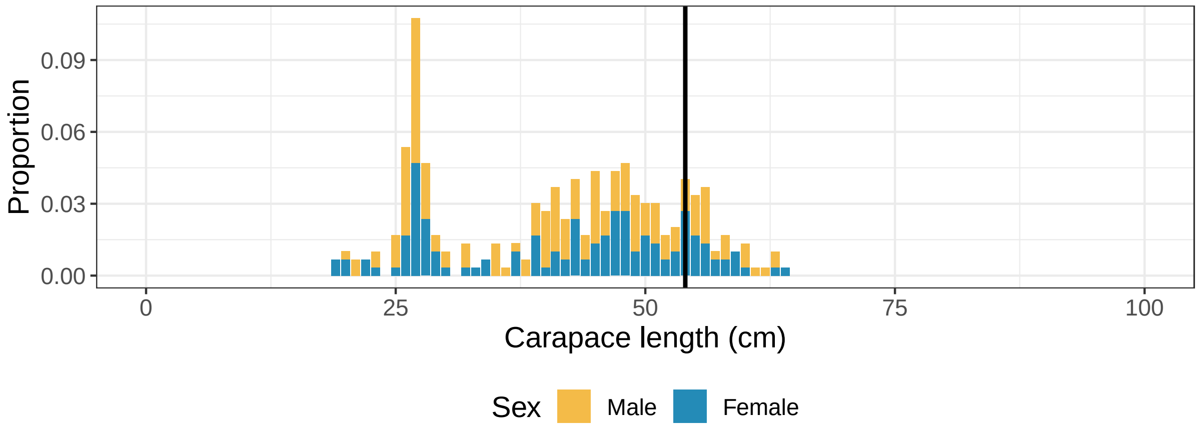


Figure F.15: Length compositions of male and female mud bugs from Jones (1988)

F.6 Biological data

Biological data and relationships were the same as those used in Section 3.1.4 unless otherwise stated.

Stock Synthesis was configured as a two-sex model for sand and mud bugs. Male and female specific growth curves were input for sand Section F.16 and mud bugs Section F.17 from Courtney (1997).

F.6.1 Growth

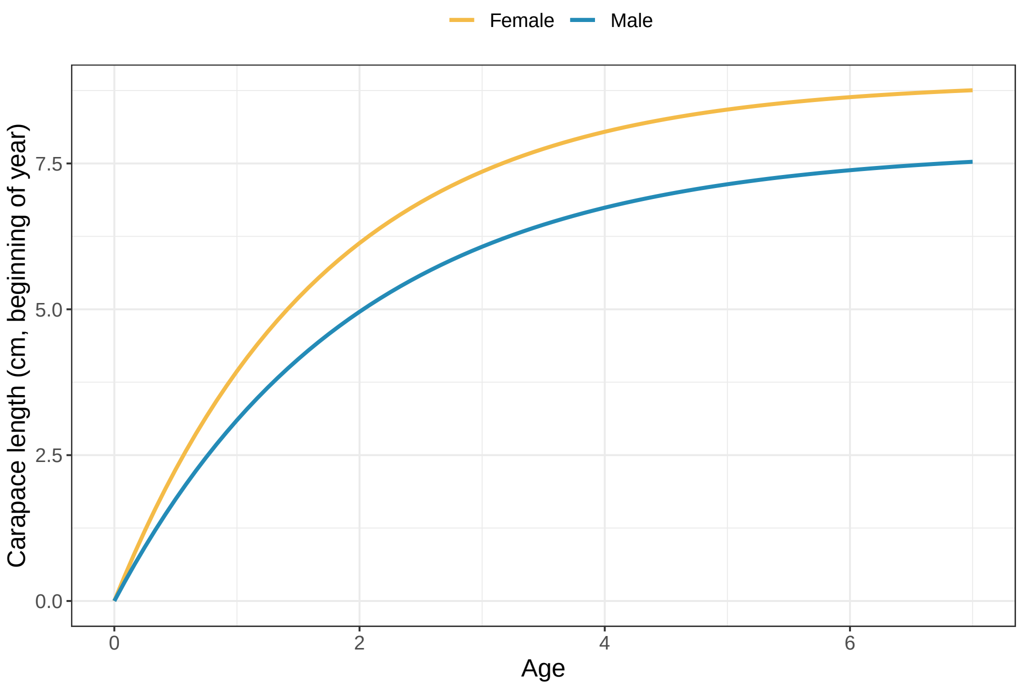


Figure F.16: Fixed length-at-age growth curve for males and females applied to the annual and monthly sand bug models

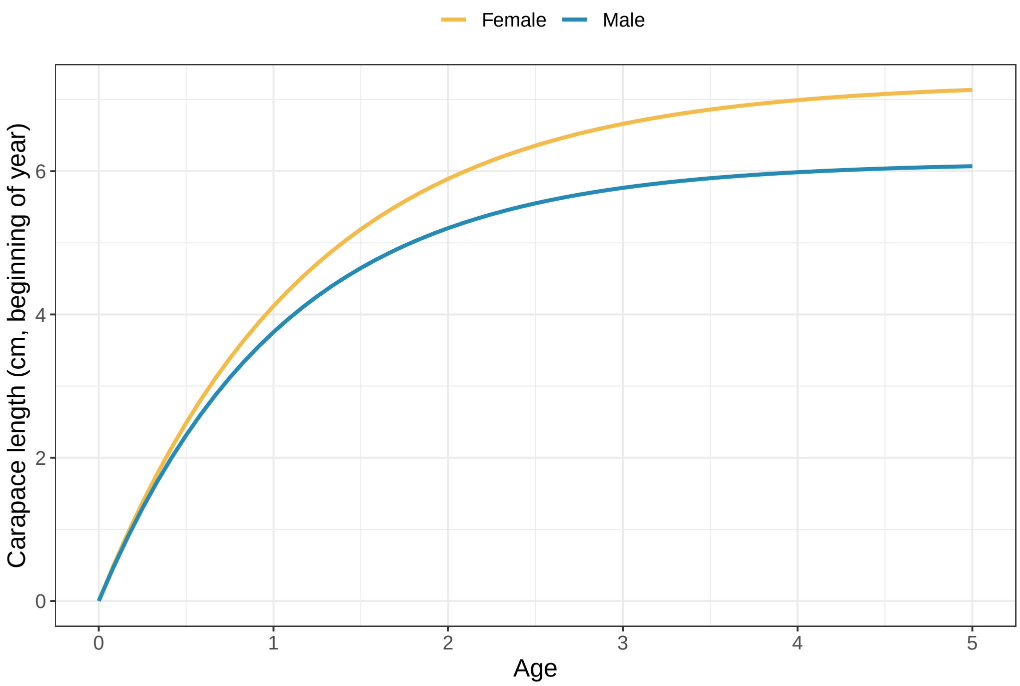


Figure F.17: Fixed length-at-age growth curve for males and females applied to the annual and monthly mud bug models

F.7 Model outputs

The parameter estimates of annual Stock Synthesis sand and mud Scenario 1 models were listed in Tables F.7 and F.8, respectively. The comparison of parameter estimates amongst the 24 annual sand and mud bug scenarios are shown in Figures F.41 and F.42, respectively.

The parameter estimates of the monthly Stock Synthesis sand and mud bug Scenario 1 models were listed in Tables F.9 and F.10. The comparison of parameter estimates amongst the 24 monthly sand and mud bug scenarios are shown in Figures F.43 and F.44, respectively.

F.7.1 Model parameters

Table F.7: Summary of parameter estimates from the Stock Synthesis annual sand bug Scenario 1 population model

Parameter	Estimate	Standard deviation
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1968)	9.71	0.17
Beverton-Holt steepness parameter	0.9	0.27
Additional esitmated error for survey post2004 fleet index	0.07	0.08
Additional esitmated error for commercial prawn pre2004 fleet catch rate	0	0
Additional esitmated error for commercial prawn post2004 fleet catch rate	0	0
Commercial survey pre2004 fleet selectivity inflection (cm)	7.11	0.23
Commercial survey pre2004 fleet selectivity width (cm)	2.15	0.11
Commercial survey post2004 fleet selectivity inflection (cm)	6.61	0.19
Commercial survey post2004 fleet selectivity width (cm)	1.92	0.09

Table F.8: Summary of parameter estimates from the Stock Synthesis annual mud bug scenario 1 population model

Parameter	Estimate	Standard deviation
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1968)	10.3	0.45
Beverton-Holt steepness parameter	0.59	0.22
Additional esitmated error for commercial pre2004 fleet catch rate	0	0
Additional esitmated error for commercial post2004 fleet catch rate	0	0
Commercial survey pre2004 fleet selectivity inflection (cm)	3.71	0.22
Commercial survey post2004 fleet selectivity width (cm)	0.75	0.23

Table F.9: Summary of parameter estimates from the Stock Synthesis monthly sand bug scenario 1 population model. Model did not converge and did not produce standard deviations for the parameters

Parameter	Estimate	Standard deviation
Recruitment distribution parameter for January	-98.05	0
Recruitment distribution parameter for February	-14.66	0
Recruitment distribution parameter for March	-28.54	0
Recruitment distribution parameter for April	-81.84	0
Recruitment distribution parameter for May	-0.2	0
Recruitment distribution parameter for June	-84.86	0
Recruitment distribution parameter for July	-71.44	0
Recruitment distribution parameter for August	-32.7	0
Recruitment distribution parameter for September	-6.42	0
Recruitment distribution parameter for October	55.07	0
Recruitment distribution parameter for November	83.24	0
Recruitment distribution parameter for December	-46.23	0
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1968)	9.8	0
Beverton-Holt steepness parameter	0.94	0
Additional esitmated error for survey post2004 fleet index	0.06	0
Additional esitmated error for commercial prawn pre2004 fleet catch rate	0.07	0
Additional esitmated error for commercial prawn post2004 fleet catch rate	0.04	0
Commercial survey pre2004 fleet selectivity inflection (cm)	6.63	0
Commercial survey pre2004 fleet selectivity width (cm)	1.78	0
Commercial survey post2004 fleet selectivity inflection (cm)	6.27	0
Commercial survey post2004 fleet selectivity width (cm)	1.57	0

Table F.10: Summary of parameter estimates from the Stock Synthesis monthly mud bug scenario 1 population model. Model did not converge and did not produce standard deviations for the parameters

Parameter	Estimate	Standard deviation
Recruitment distribution parameter for January	42.42	0
Recruitment distribution parameter for February	-9.1	0
Recruitment distribution parameter for March	-17.55	0
Recruitment distribution parameter for April	-11.27	0
Recruitment distribution parameter for May	-10.26	0
Recruitment distribution parameter for June	-10.81	0
Recruitment distribution parameter for July	-9.55	0
Recruitment distribution parameter for August	-10.87	0
Recruitment distribution parameter for September	-10.07	0
Recruitment distribution parameter for October	-9.98	0
Recruitment distribution parameter for November	-3.02	0
Recruitment distribution parameter for December	8.28	0
Beverton-Holt unfished recruitment (logarithm of the number of recruits in 1968)	20.92	0
Beverton-Holt steepness parameter	0.24	0
Additional esitmated error for commercial pre2004 fleet catch rate	0.19	0
Additional esitmated error for commercial post2004 fleet catch rate	0.21	0
Commercial survey pre2004 fleet selectivity inflection (cm)	3.96	0
Commercial survey post2004 fleet selectivity width (cm)	1	0

F.7.2 Model fits

All annual and monthly scenarios of Stock Synthesis models had poor fits for sand and mud bug models. Evidence was present to suggest abundance indices were over fit (see Figures F.18 and F.19). For all scenarios in all models (annual and monthly sand and mud bug) steepness consistently estimated high with wide uncertainty (see Figures F.41, F.42, F.43, and F.44). For monthly Stock Synthesis models, seasonal recruitment parameters estimated cleanly, but only after widening their bounds beyond what is recommended in the SS user manual (see Figures F.31 and F.32).

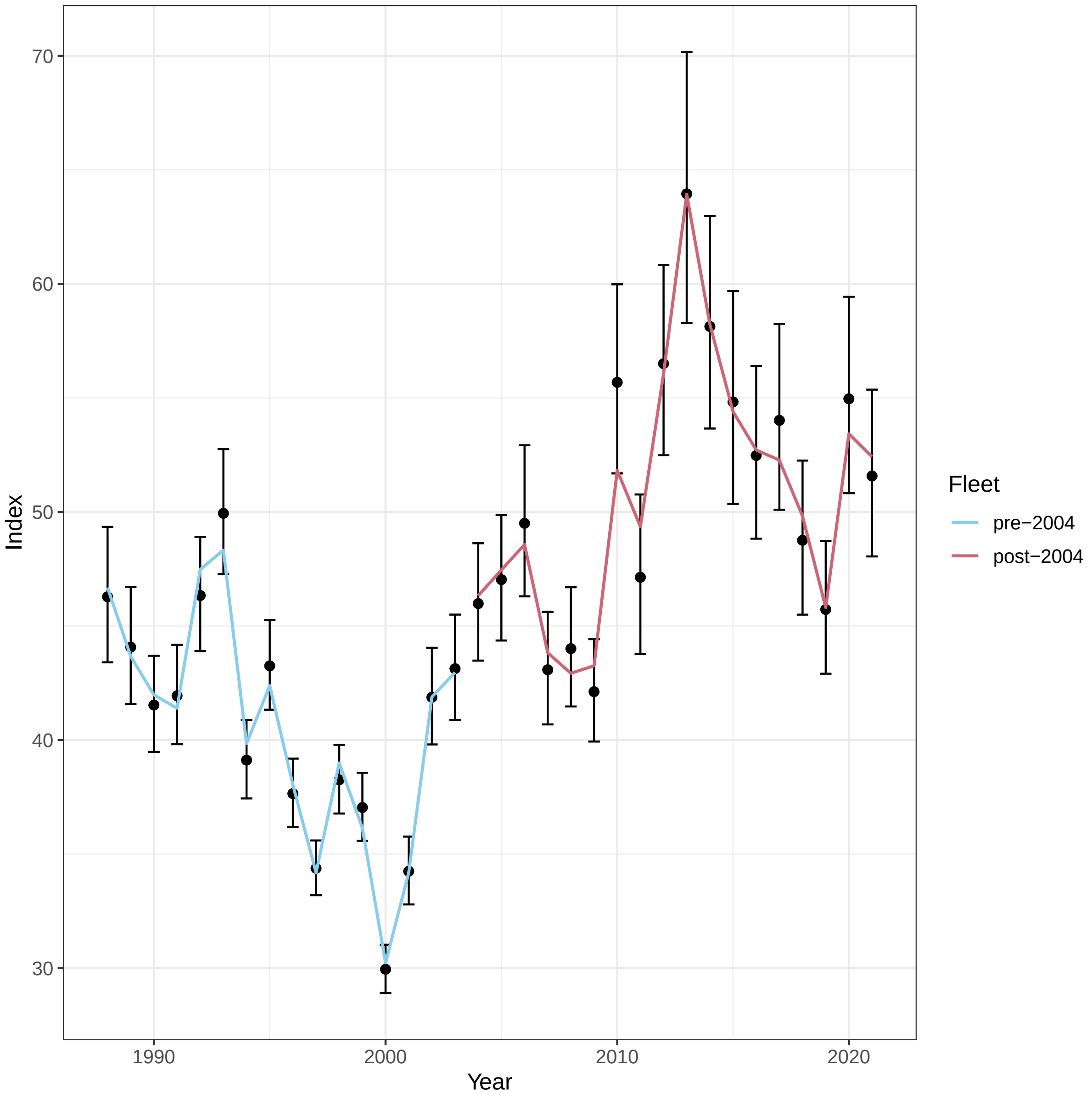


Figure F.18: Fits to catch rate data for scenario 1 annual sand bug commercial pre-2004 and post-2004 prawn fleets

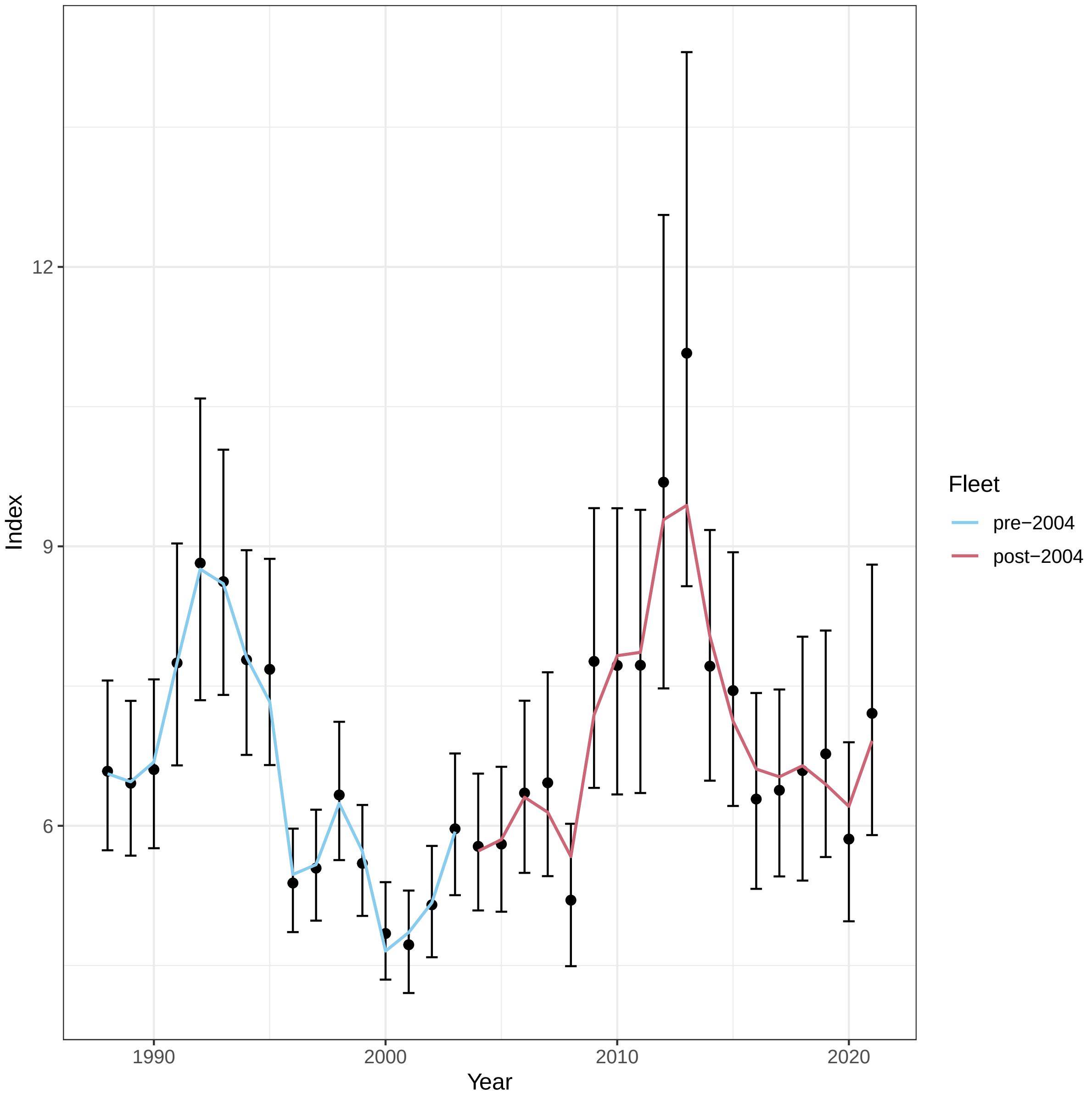


Figure F.19: Fits to catch rate data for scenario 1 annual mud bug commercial pre-2004 and post-2004 fleets

F.7.3 Length compositions

Length frequency fits for sand bug pre-2004 and post-2004 survey fleets are shown in Figures F.20 and F.21. Length frequency fits for the mud bug survey fleet are shown in F.22.

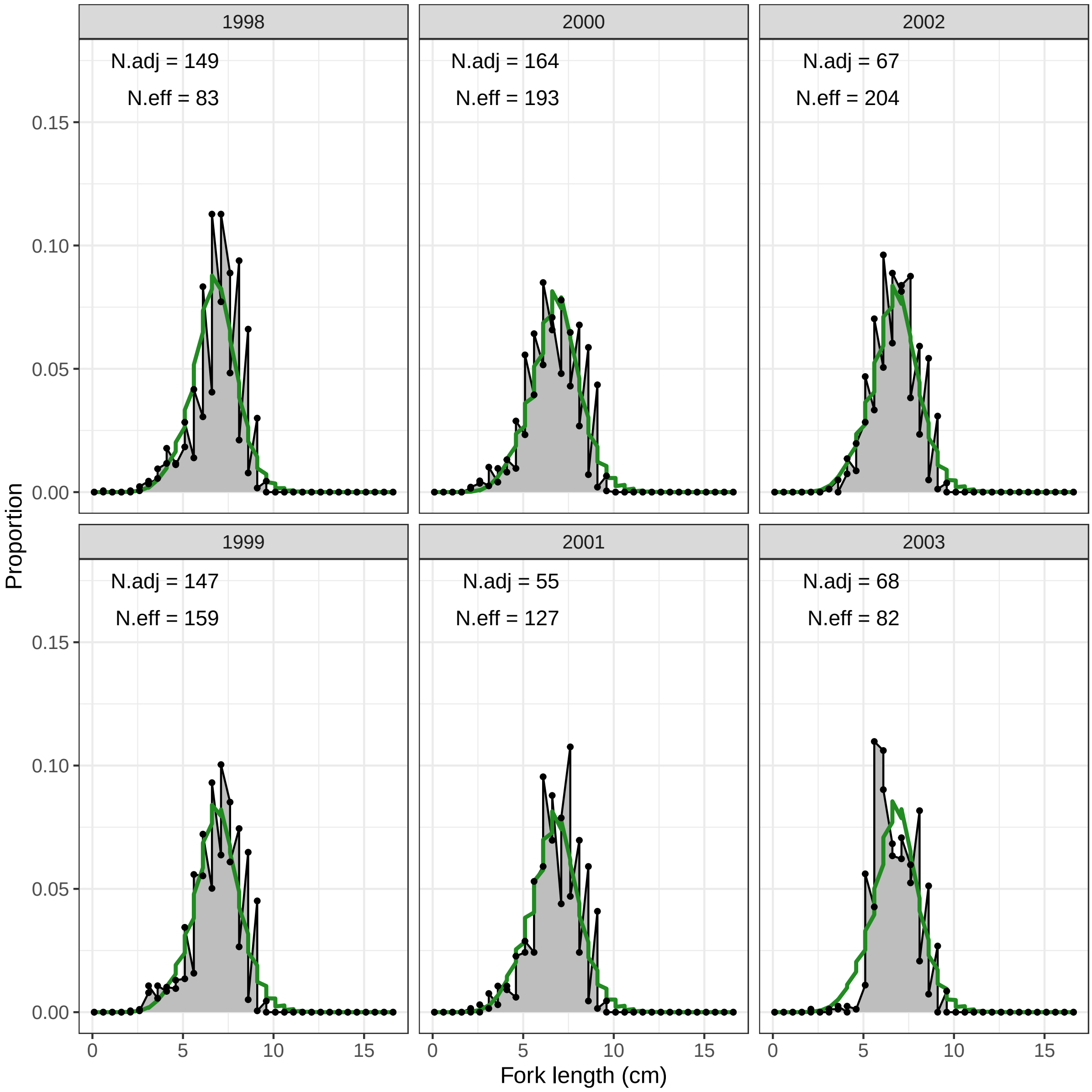


Figure F.20: Fits to length structures for sand bug survey fleet pre-2004

Note: 'N adj.' is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the McAllister-Iannelli tuning method

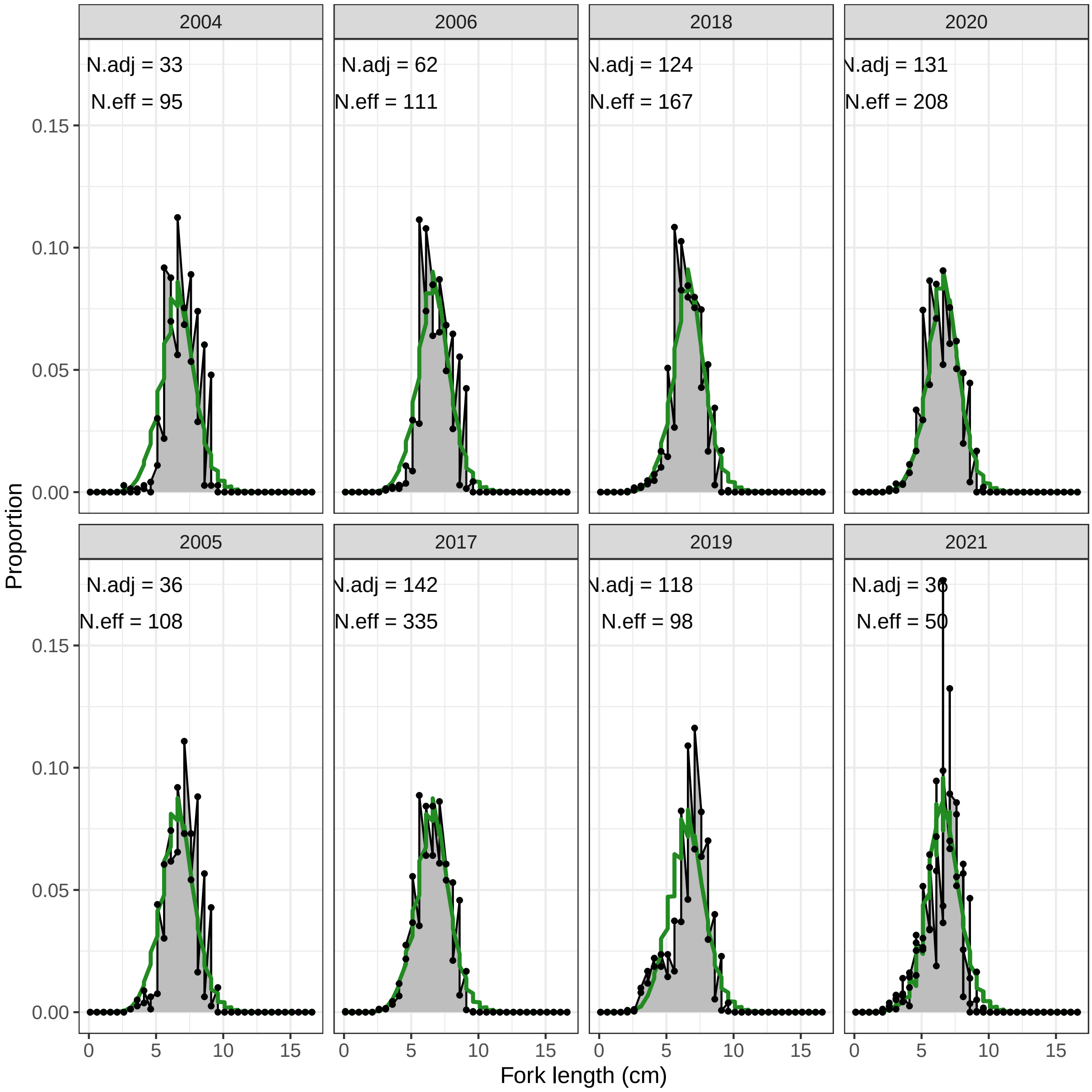


Figure F.21: Fits to length structures for sand bug survey fleet for post-2004

Note: 'N adj.' is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the McAllister-Iannelli tuning method

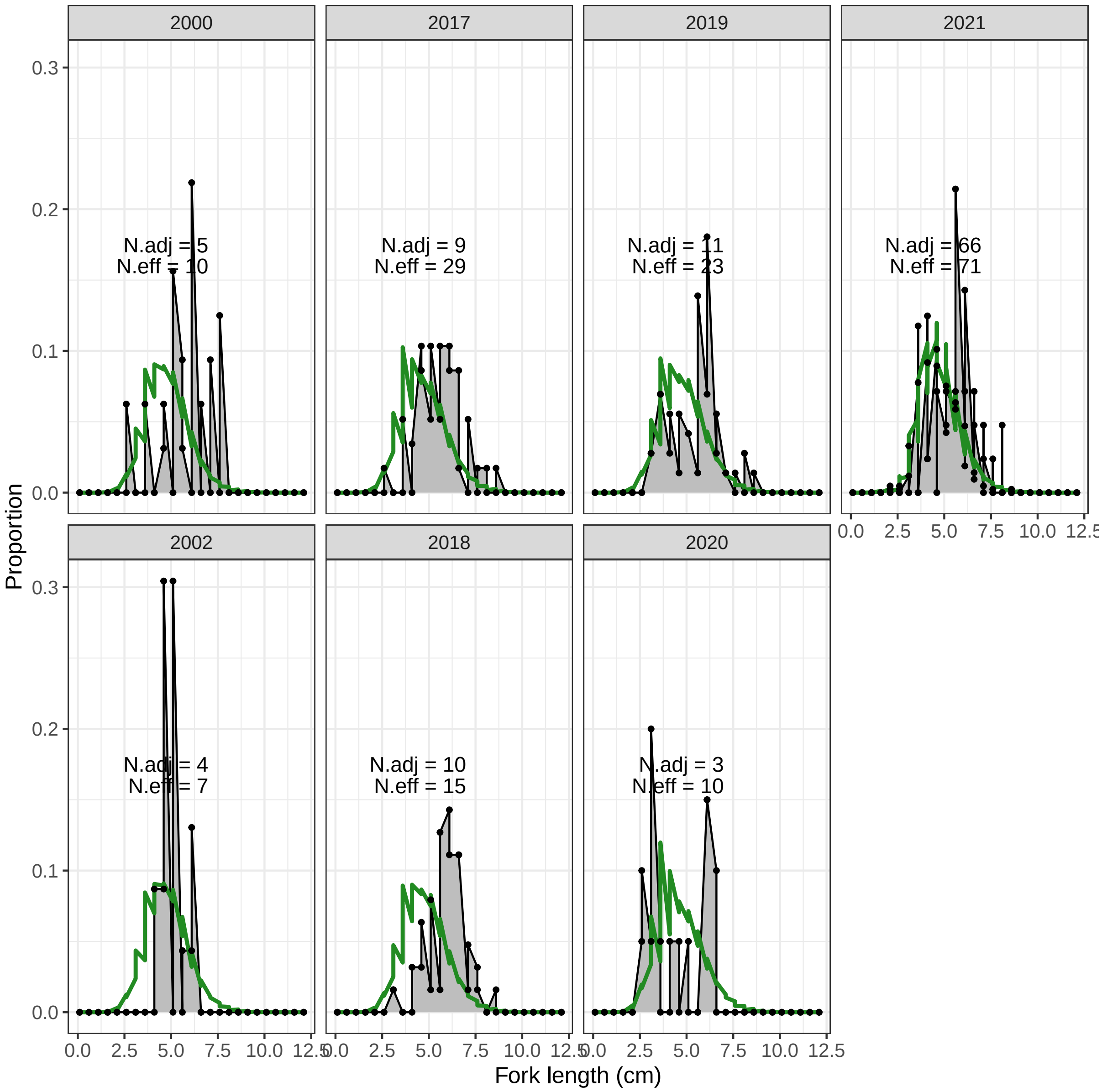


Figure F.22: Fits to length structures for mud bug survey fleet pre- and post-2004

Note: 'N adj.' is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the McAllister-Iannelli tuning method

F.7.4 Selectivity

Selectivity of sand and mud bugs were estimated within the SS model. Two selectivity curves (i.e., pre-2004 and post-2004) were estimated from fishery independent data for sand bugs when using split catch rates. Female and male sand bug selectivity are shown in Figures F.24 and F.25 for the pre-2004 fleet, respectively. Female and male sand bug selectivity are shown in Figures F.26 and F.27 for the post-2004 fleet, respectively.

A single selectivity curve was utilised for Stock Synthesis mud bug models given limited data. Female and male mud bug selectivity are shown in Figures F.29 and F.30.

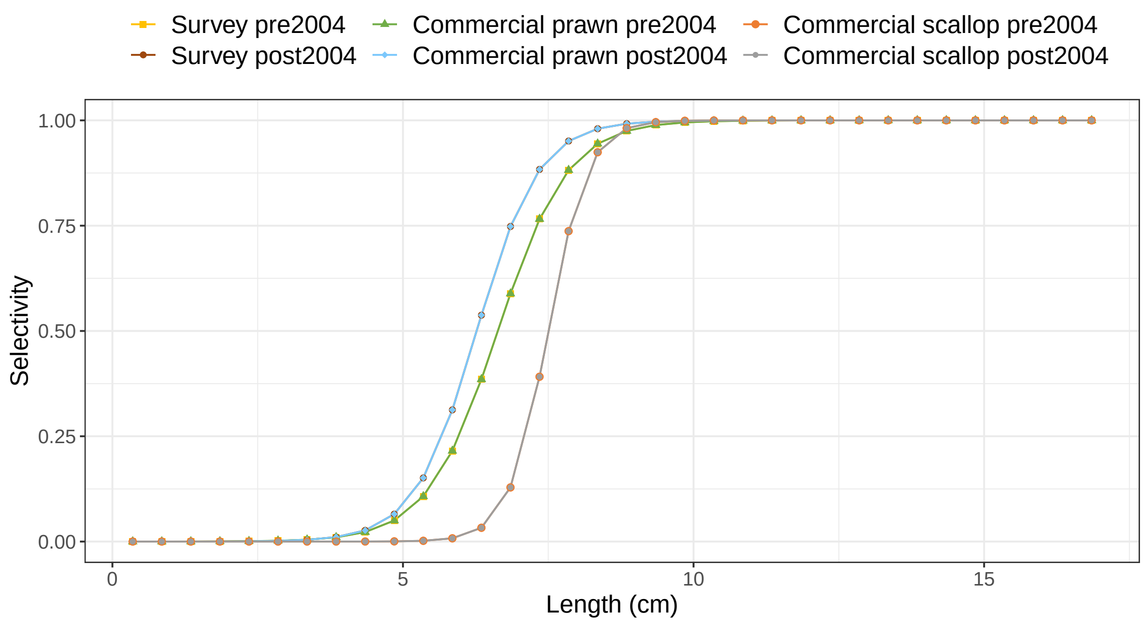


Figure F.23: Selectivity curves for all fleets in Scenario 1 monthly Stock Synthesis sand bug model

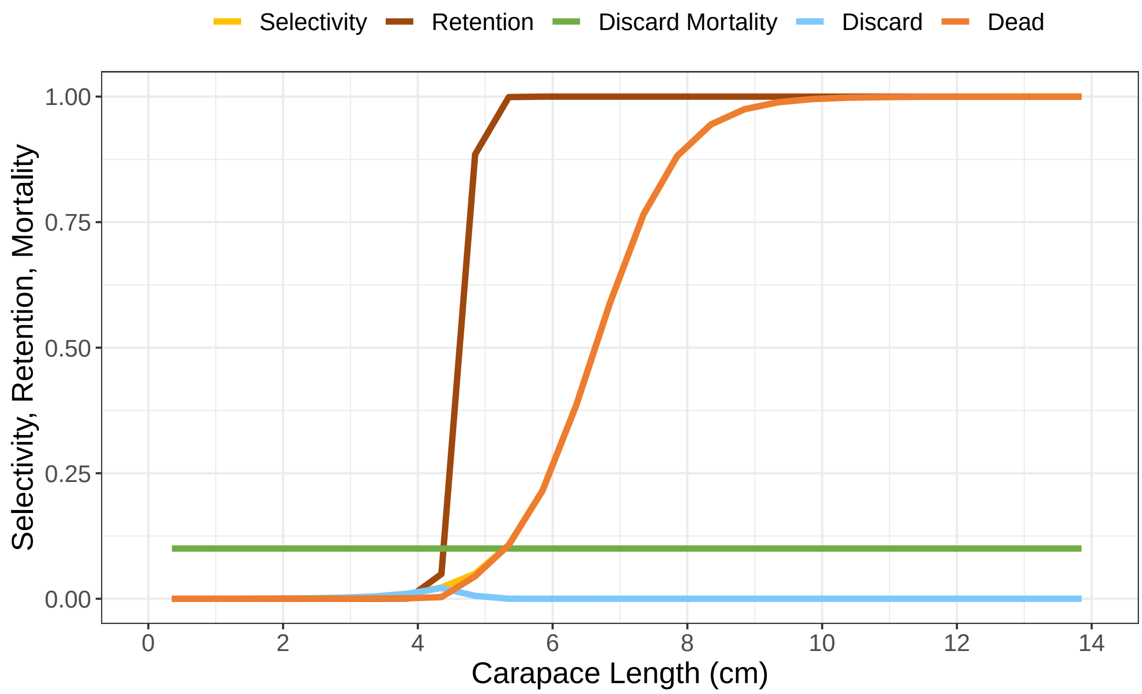


Figure F.24: Monthly Scenario 1 Stock Synthesis estimated selectivity, discard, discard mortality and retention for female sand bugs in the pre-2004 fleet for the east coast stock

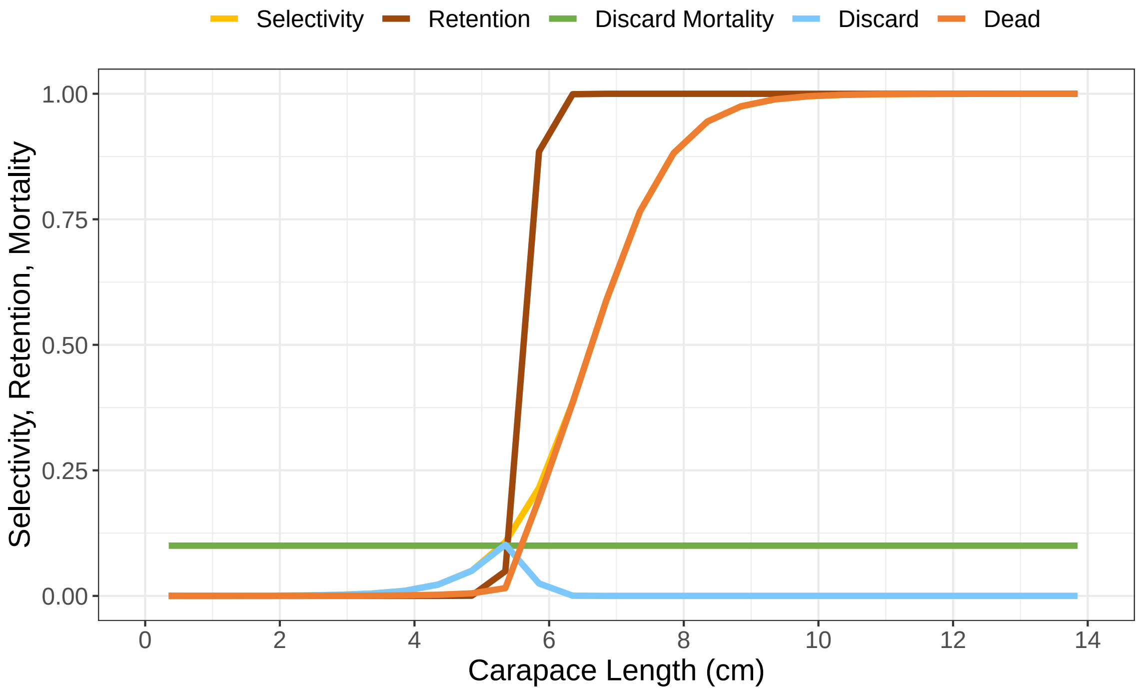


Figure F.25: Monthly scenario 1 Stock Synthesis estimated selectivity, discard, discard mortality and retention for male sand bugs in the pre-2004 fleet for the east coast stock

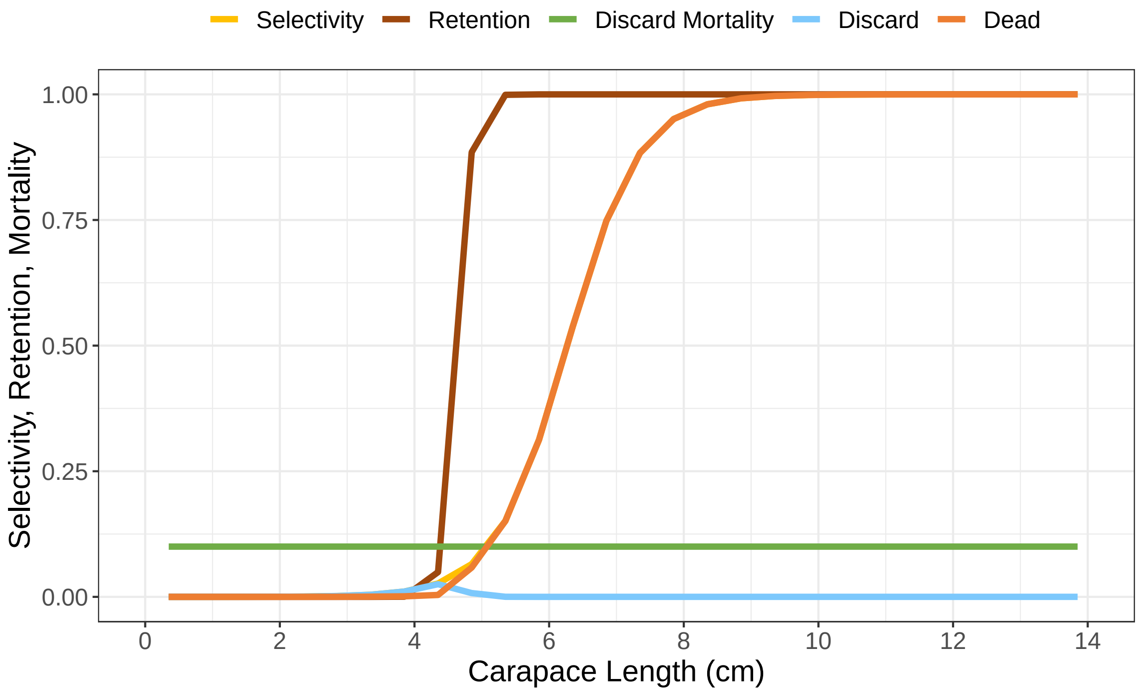


Figure F.26: Monthly scenario 1 Stock Synthesis estimated selectivity, discard, discard mortality and retention for female sand bugs in the post-2004 fleet for the east coast stock

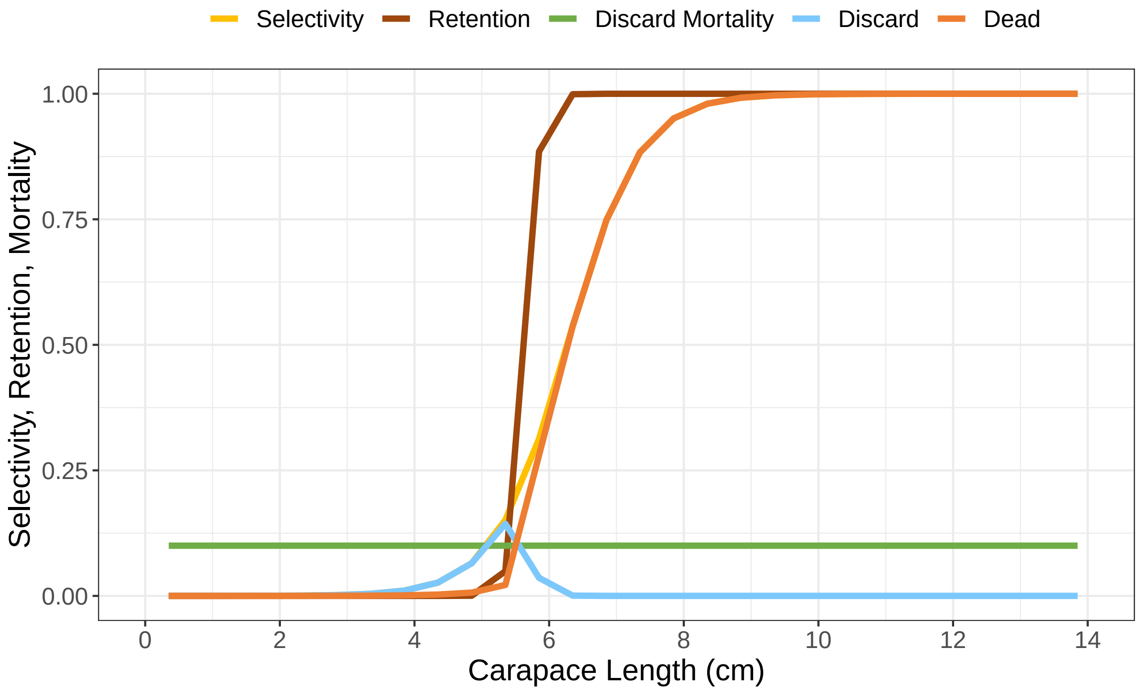


Figure F.27: Monthly scenario 1 Stock Synthesis estimated selectivity, discard, discard mortality and retention for male sand bugs in the post-2004 fleets for the east coast stock

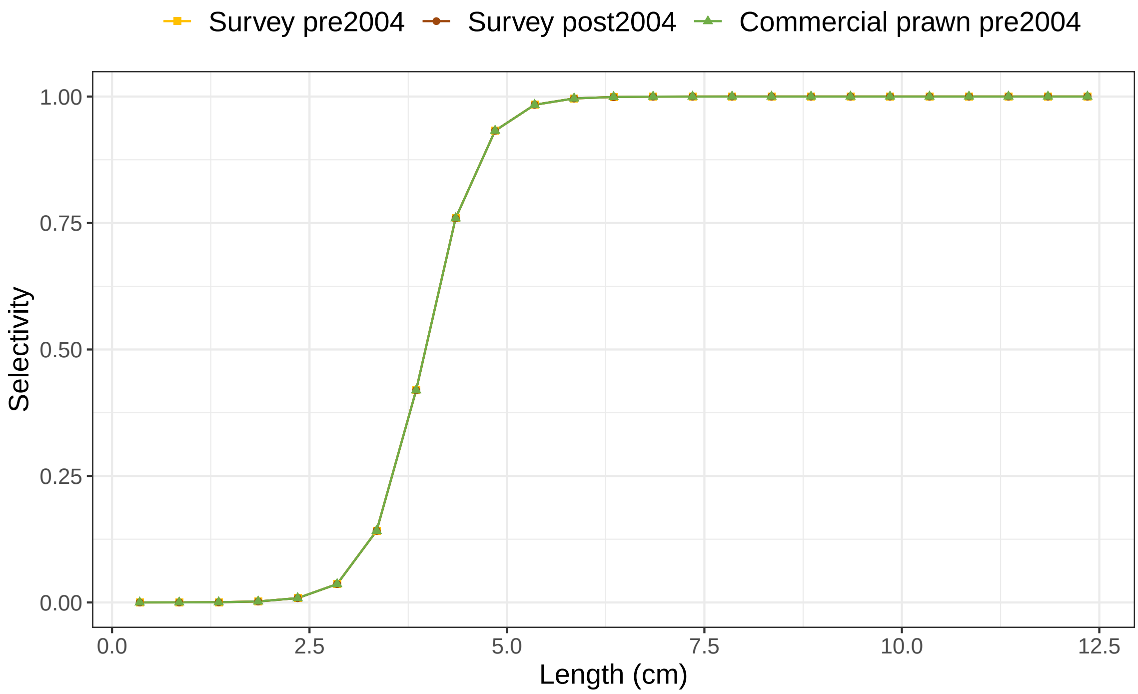


Figure F.28: Selectivity curves for all fleets in scenario 1 monthly Stock Synthesis sand bug model

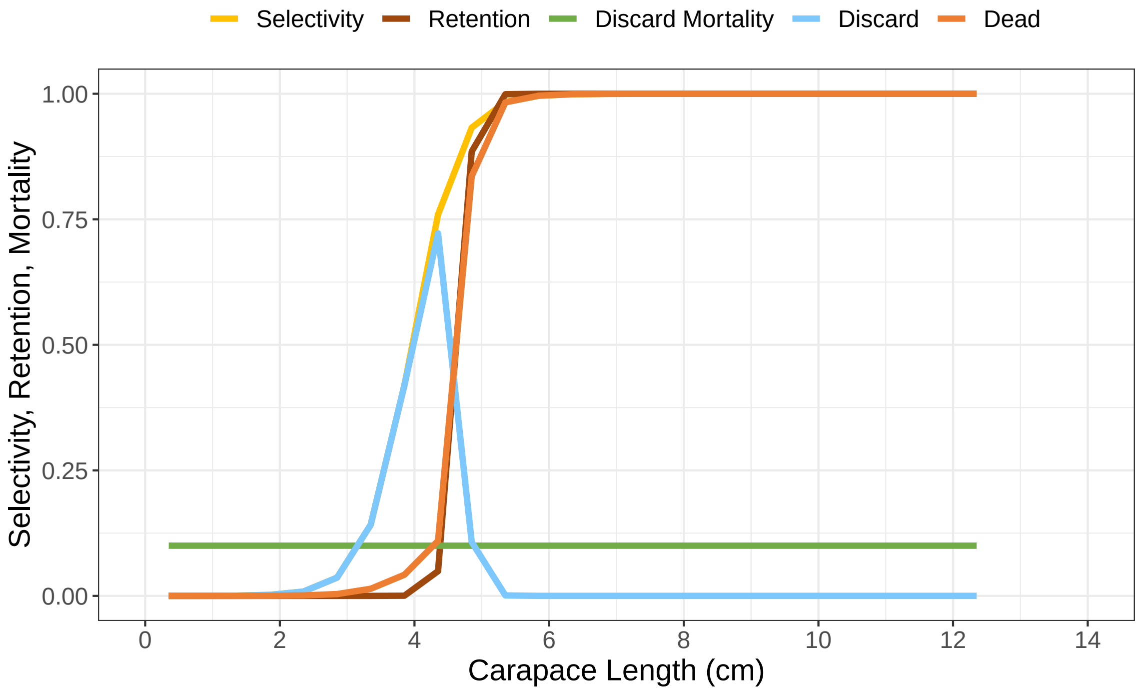


Figure F.29: Monthly scenario 1 Stock Synthesis estimated selectivity, discard, discard mortality and retention for female mud bugs in the pre- and post-2004 fleets for the east coast stock

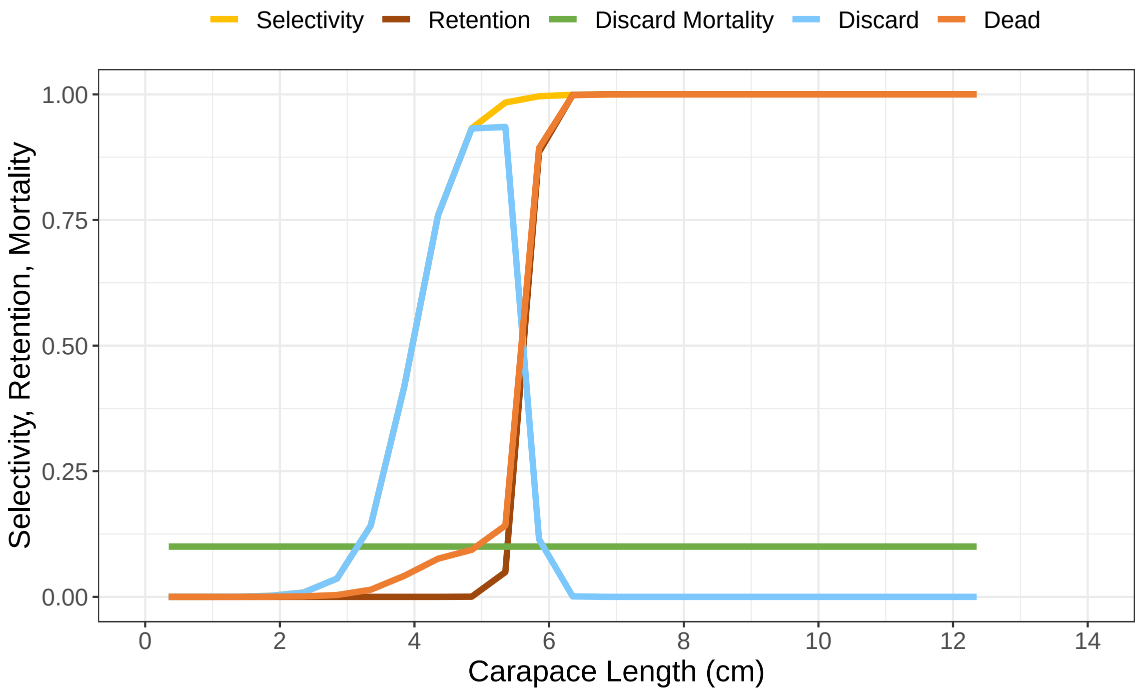


Figure F.30: Monthly scenario 1 Stock Synthesis estimated selectivity, discard, discard mortality and retention for male mud bugs in the pre- and post2004 fleets for the east coast stock

F.7.5 Recruitment distribution

For monthly Stock Synthesis models the apportionment of recruitment throughout months was estimated within the model. The distribution of recruits for monthly sand and mud bugs is shown in Figures F.31 and F.32.

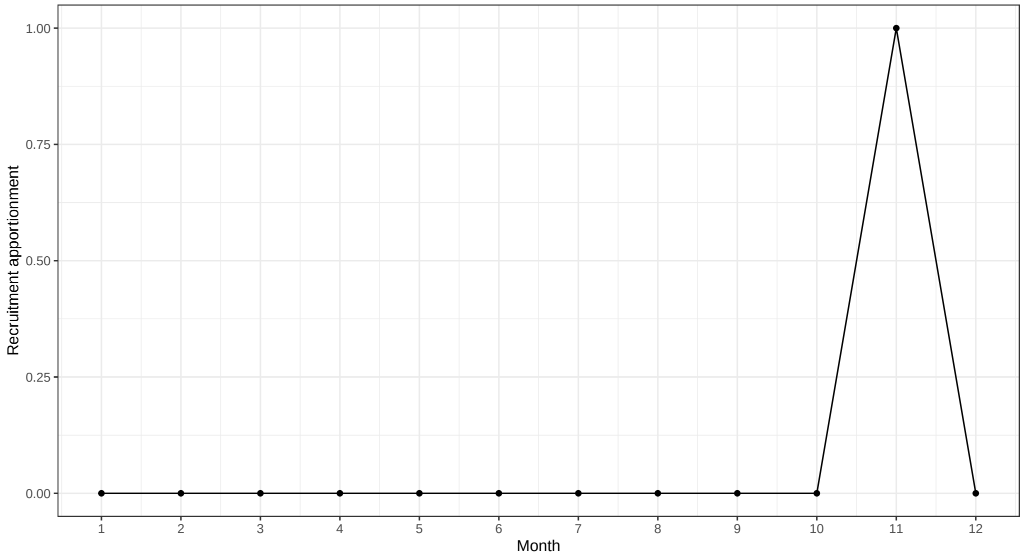


Figure F.31: Stock Synthesis estimated monthly recruitment pattern for sand bugs from scenario 1

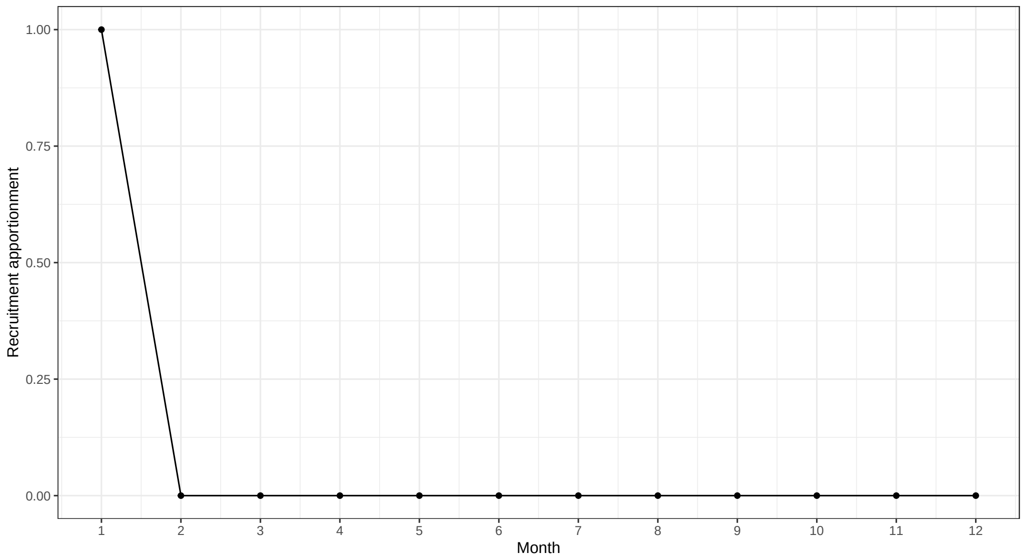


Figure F.32: Stock Synthesis estimated monthly recruitment pattern for mud bugs from scenario 1

F.7.6 Biomass

F.7.6.1 Annual sand

Annual sand bug Stock Synthesis models were sensitivity tested against split or continuous catch rates, four different harvest reconstructions (i.e., 100%, pattern, 75% and 125%), and three different levels of natural mortality (i.e., low = 0.72, medium = 0.92 and high = 1.12).

Comparing annual sand Stock Synthesis models with split and continuous catch rates showed different estimates of biomass. When Stock Synthesis was configured for split catch rates (scenario 1), biomass estimates increased from 33% to 42% when compared to continuous catch rates (scenario 13). When split catch rates were combined with different harvest reconstructions scenarios (i.e., scenario 1: 100%, scenario 4: pattern, scenario 7: 75% and scenario 10: 125%) biomass estimates were 42%, 41%, 44% and 41%, respectively. When split catch rates and the 100% harvest scenario were tested across different levels of natural mortality (i.e., scenario 2: low = 0.72, scenario 1: medium = 0.92 and scenario 3: high = 1.12) biomass estimates were 30%, 42% and 54%, respectively. Therefore, biomass estimates for annual sand bug Stock Synthesis models were most sensitive to natural mortality, followed split or continuous catch rates whilst harvest had little effect (see Figure F.33).

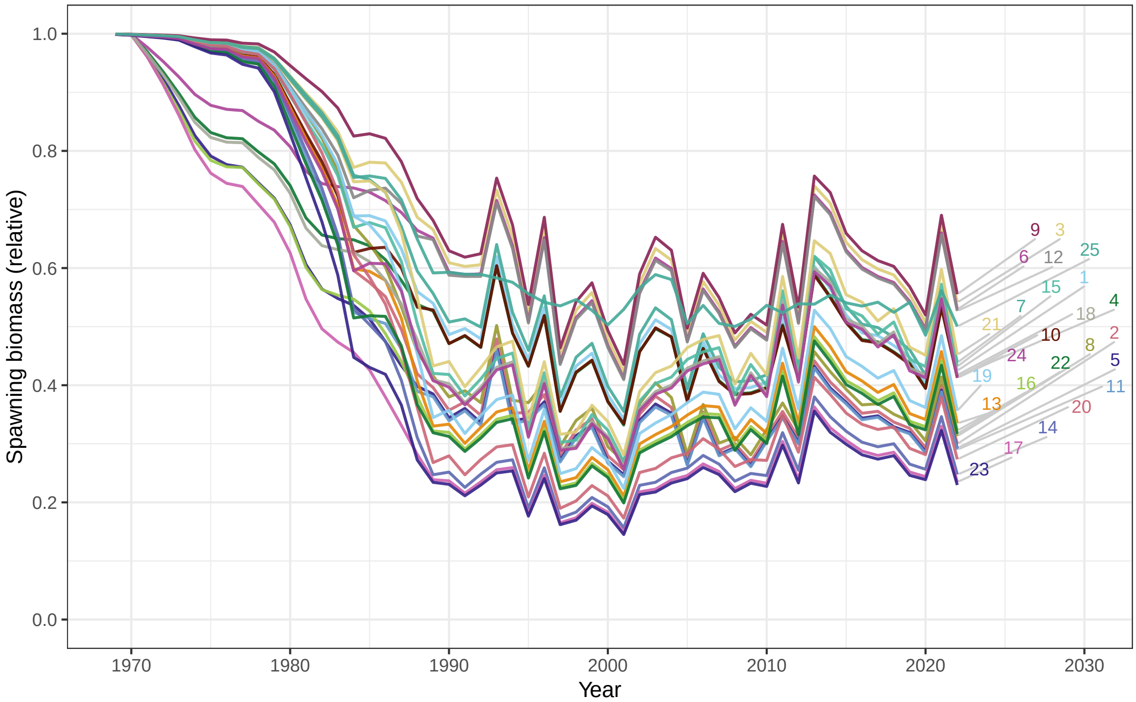


Figure F.33: Estimated biomass trajectory relative to virgin sand bug biomass for all 25 annual Stock Synthesis models

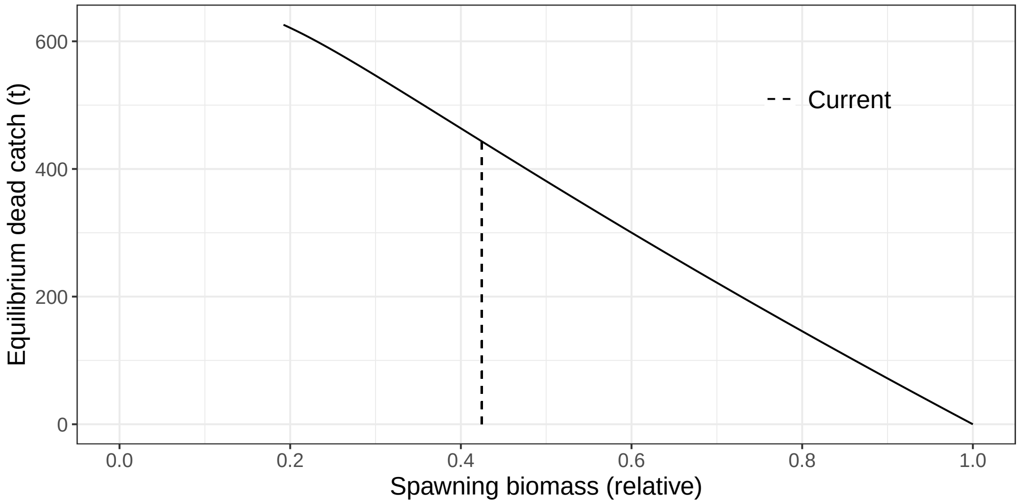


Figure F.34: Equilibrium yield curve for sand bugs based on annual Stock Synthesis model scenario 1. This indicates non-convergence of the MSY calculation.

F.7.6.2 Annual mud

Annual mud bug Stock Synthesis models were sensitivity tested against split or continuous catch rates, four different harvest reconstructions (i.e., 100%, pattern, 75% and 125%), and three different levels of natural mortality (i.e., low = 1.06, medium = 1.26 and high = 1.46).

Comparing annual mud Stock Synthesis models with split and continuous catch rates showed similar estimates of biomass. When Stock Synthesis was configured for split catch rates (scenario 1), biomass estimates decreased from 81% to 79% when compared to continuous catch rates (scenario 13). When split catch rates were combined with different harvest reconstructions scenarios (i.e., scenario 1: 100%, scenario 4: pattern, scenario 7: 75% and scenario 10: 125%) biomass estimates were 79%, 79%, 80% and 81%, respectively. When split catch rates and the 100% harvest scenario were tested across different levels of natural mortality (i.e., scenario 2: low = 1.06, scenario 1: medium = 1.26 and scenario 3: high = 1.46) biomass estimates were 79%, 79% and 81%, respectively. Therefore, biomass estimates for annual mud bug Stock Synthesis models showed minimal sensitivity to either natural mortality, split or continuous catch rates or harvest (see Figure F.35).

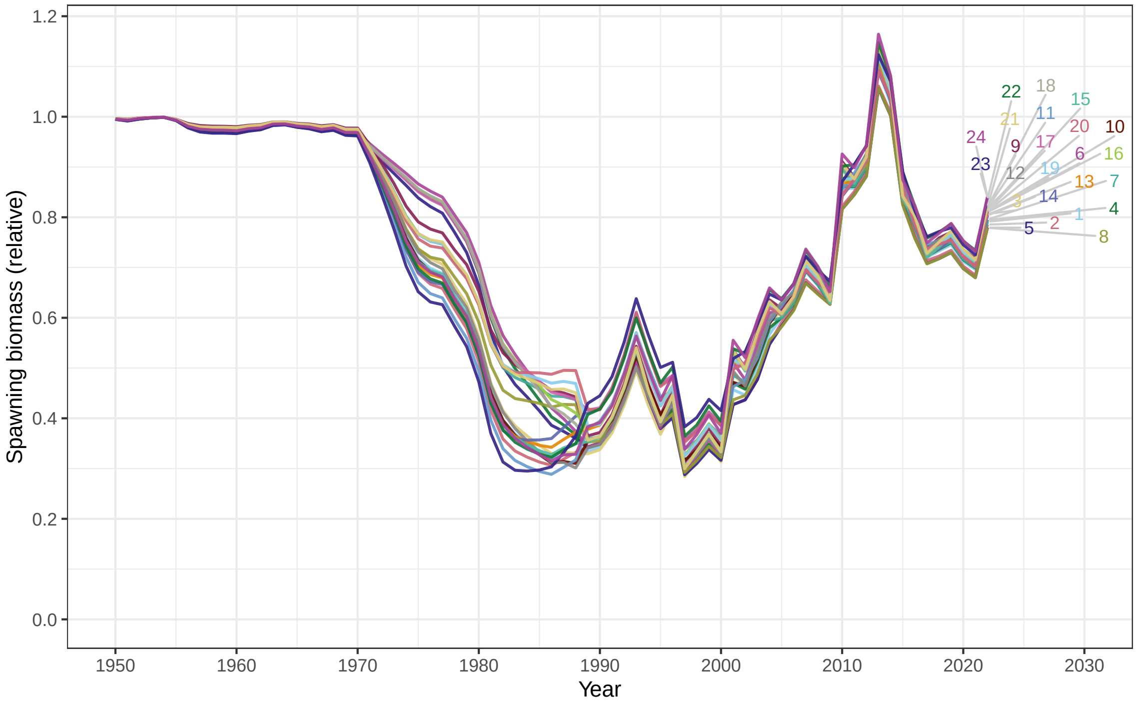


Figure F.35: Estimated biomass trajectory relative to virgin mud bug biomass for all 24 annual Stock Synthesis models

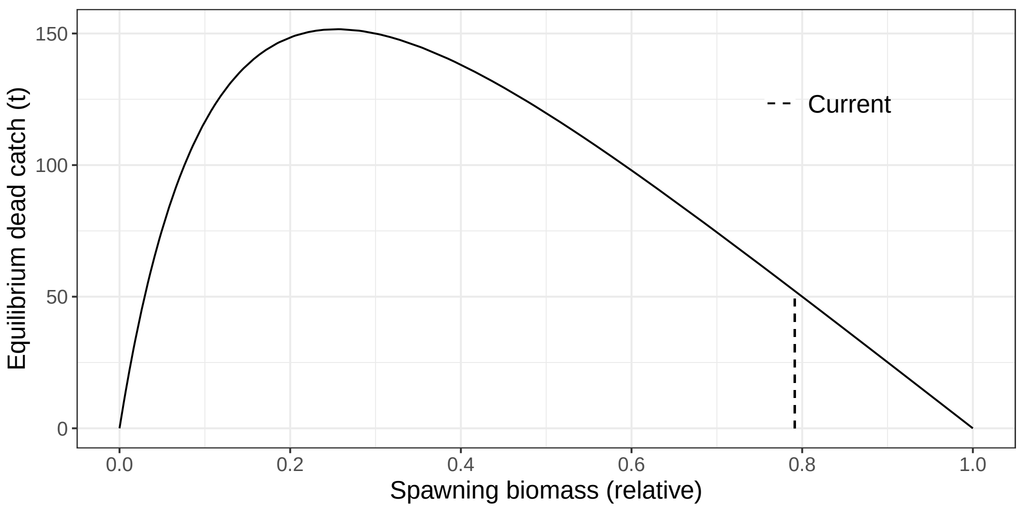


Figure F.36: Equilibrium yield curve for mud bugs based on annual Stock Synthesis model scenario 1

F.7.6.3 Monthly sand bug Stock Synthesis

Monthly sand bug Stock Synthesis models were sensitivity tested against split or continuous catch rates, four different harvest reconstructions (i.e., 100%, pattern, 75% and 125%), and three different levels of natural mortality (i.e., low = 0.72, medium = 0.92 and high = 1.12).

Comparing monthly sand bug Stock Synthesis models with split and continuous catch rates showed different estimates of biomass. When Stock Synthesis was configured for split catch rates (scenario 1), biomass estimates increased from 41% to 47% when compared to continuous catch rates (scenario 13). When split catch rates were combined with different harvest reconstructions scenarios (i.e., scenario 1:

100%, scenario 4: pattern, scenario 7: 75% and scenario 10: 125%) biomass estimates were 47%, 47%, 48% and 47%, respectively. When split catch rates and the 100% harvest scenario were tested across different levels of natural mortality (i.e., scenario 2: low = 0.72, scenario 1: medium = 0.92 and scenario 3: high = 1.12) biomass estimates were 37%, 47% and 52%, respectively. Therefore, biomass estimates for monthly sand bug Stock Synthesis models were most sensitive to natural mortality, followed by split or continuous catch rates whilst harvest had little effect (see Figure F.37).

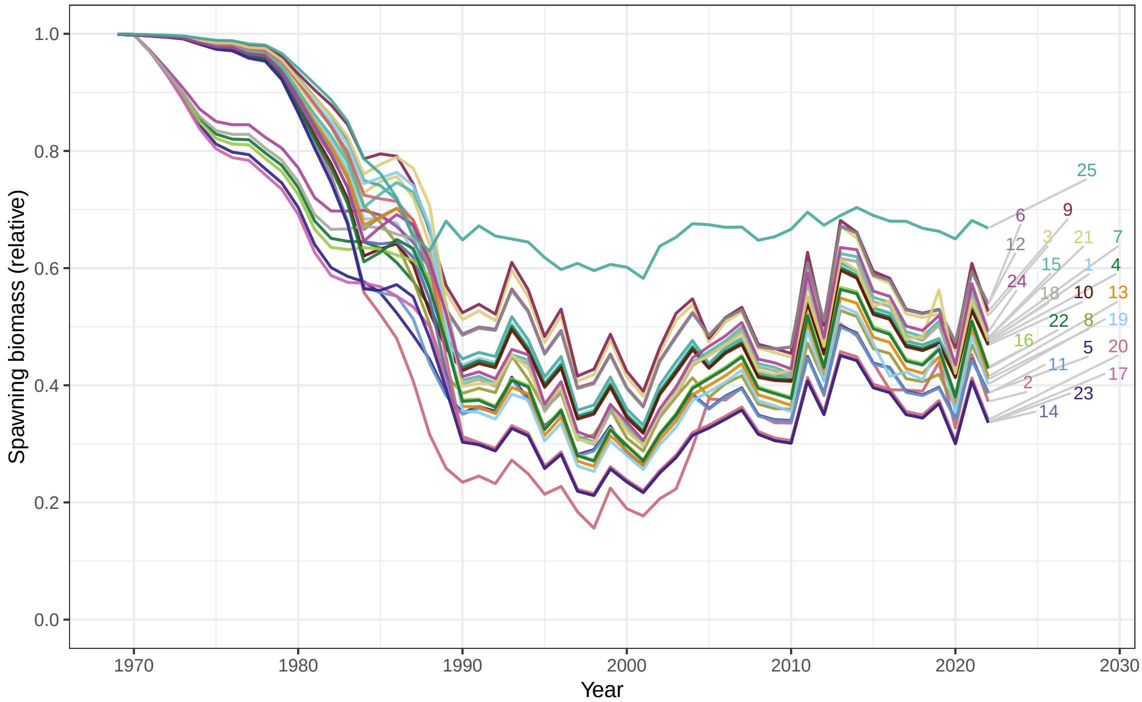


Figure F.37: Estimated biomass trajectory relative to virgin sand bug biomass for all 25 monthly Stock Synthesis models

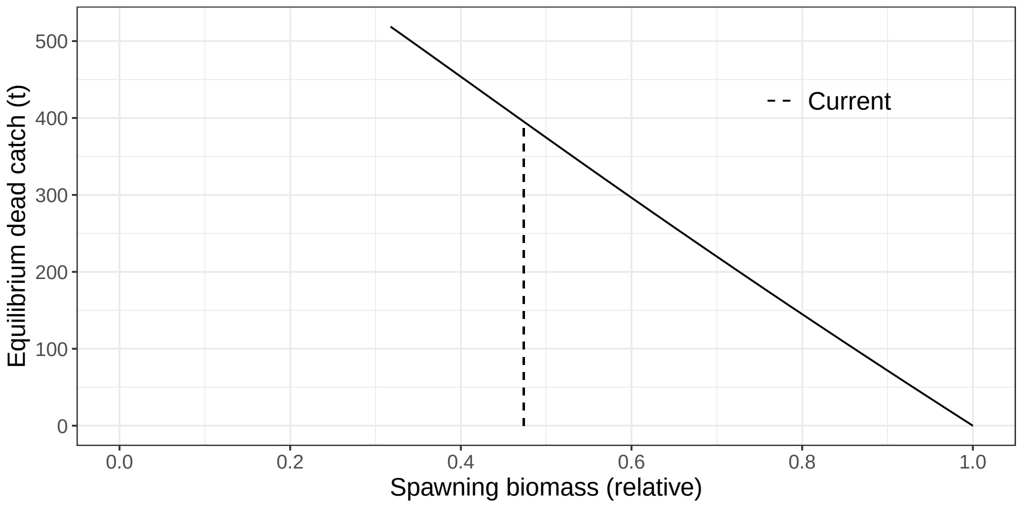


Figure F.38: Equilibrium yield curve for sand bugs based on monthly Stock Synthesis model scenario 1. This indicates non-convergence of the MSY calculation.

F.7.6.4 Monthly mud Stock Synthesis

Monthly mud bug Stock Synthesis models were sensitivity tested against split or continuous catch rates, four different harvest reconstructions (i.e., 100%, pattern, 75% and 125%), and three different levels of natural mortality (i.e., low = 1.06, medium = 1.26 and high = 1.46).

Comparing monthly mud bug Stock Synthesis models with split and continuous catch rates showed different estimates of biomass. When Stock Synthesis was configured for split catch rates (scenario 1), biomass estimates increased from 94% to 123% when compared to continuous catch rates (scenario 13). When split catch rates were combined with different harvest reconstructions scenarios (i.e., scenario 1: 100%, scenario 4: pattern, scenario 7: 75% and scenario 10: 125%) biomass estimates were 123%, 91%, 96% and 124%, respectively. When split catch rates and the 100% harvest scenario were tested across different levels of natural mortality (i.e., scenario 2: low = 1.06, scenario 1: medium = 1.26 and scenario 3: high = 1.46) biomass estimates were 112%, 123% and 98%, respectively. Therefore, biomass estimates for monthly mud bug Stock Synthesis models were sensitive to natural mortality, harvest and split or continuous catch rates (see Figure F.39).

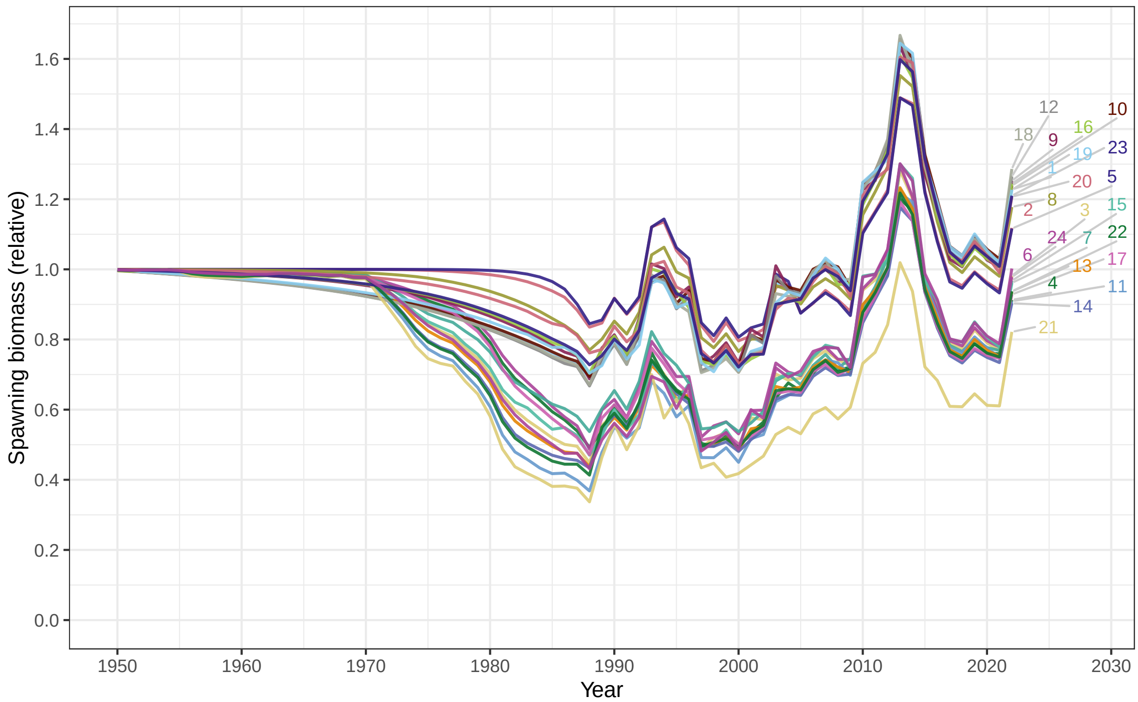


Figure F.39: Estimated biomass trajectory relative to virgin mud bug biomass for all 24 monthly Stock Synthesis models

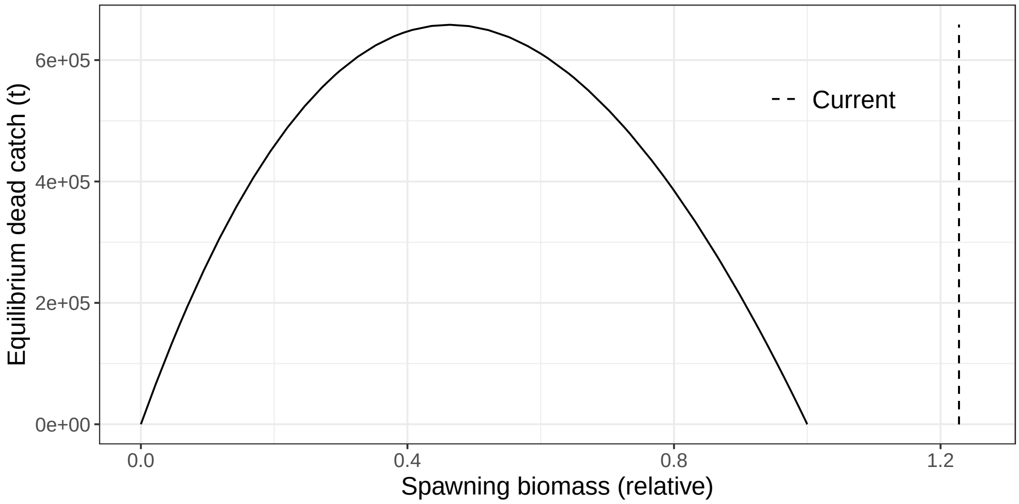


Figure F.40: Equilibrium yield curve for mud bugs based on monthly Stock Synthesis model scenario 1

F.7.7 Alternate scenario parameter estimates

Parameter estimates for all 24 annual sand and mud bug Stock Synthesis models are shown in Figures F.41 and F.42.

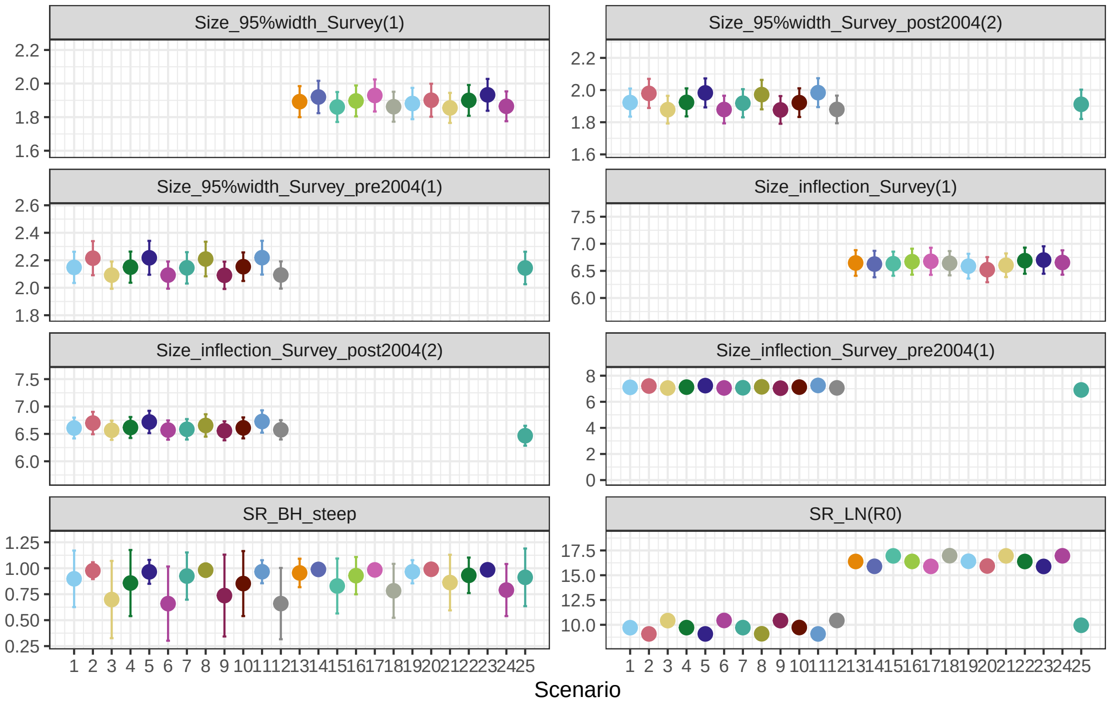


Figure F.41: Parameter estimates for all 25 annual sand bug Stock Synthesis models

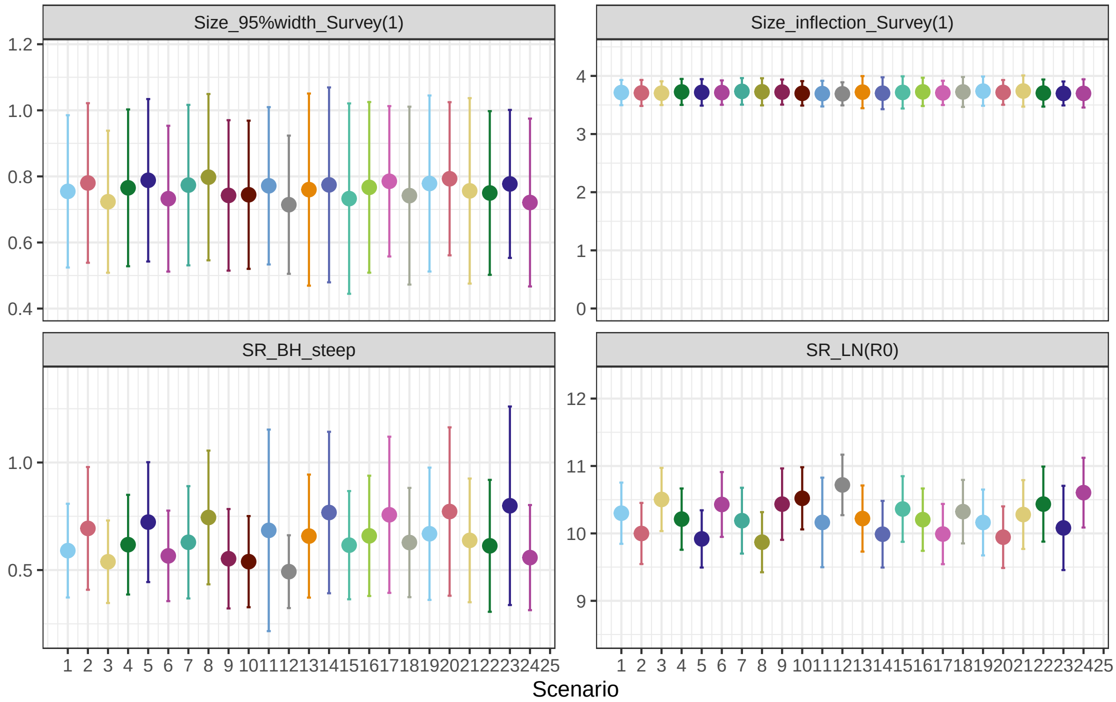


Figure F.42: Parameter estimates for all 24 annual mud bug Stock Synthesis models

Parameter estimates for all 24 monthly sand and mud bug Stock Synthesis models are shown in Figures F.43 and F.44.

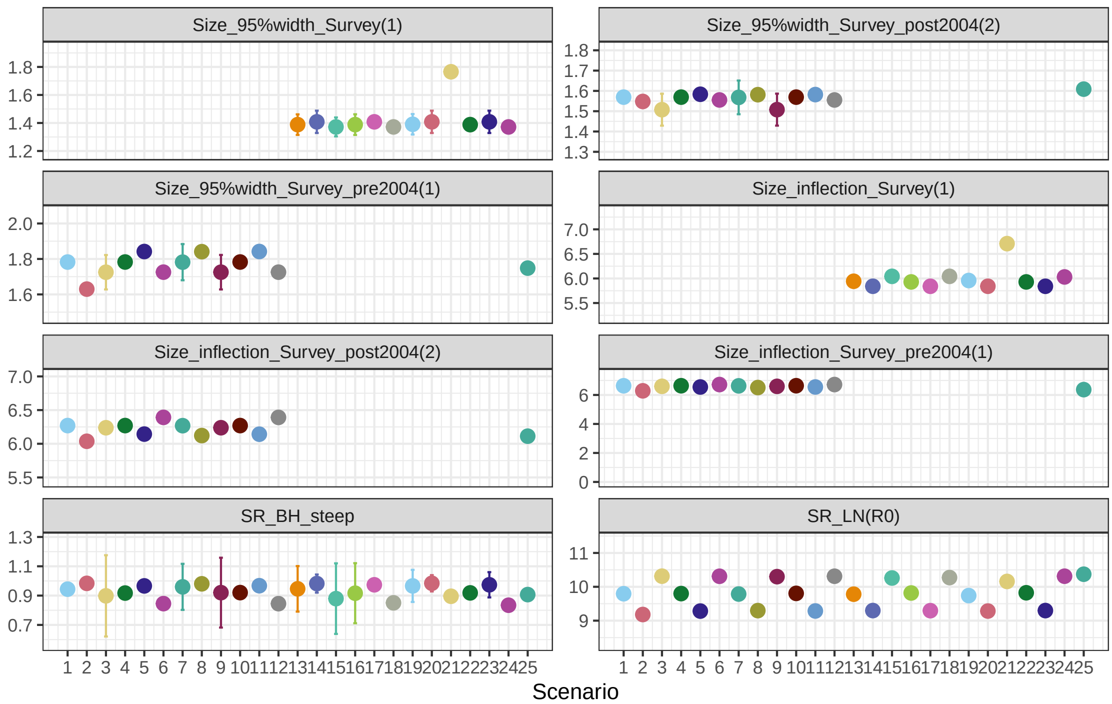


Figure F.43: Parameter estimates for all 25 monthly sand bug Stock Synthesis models

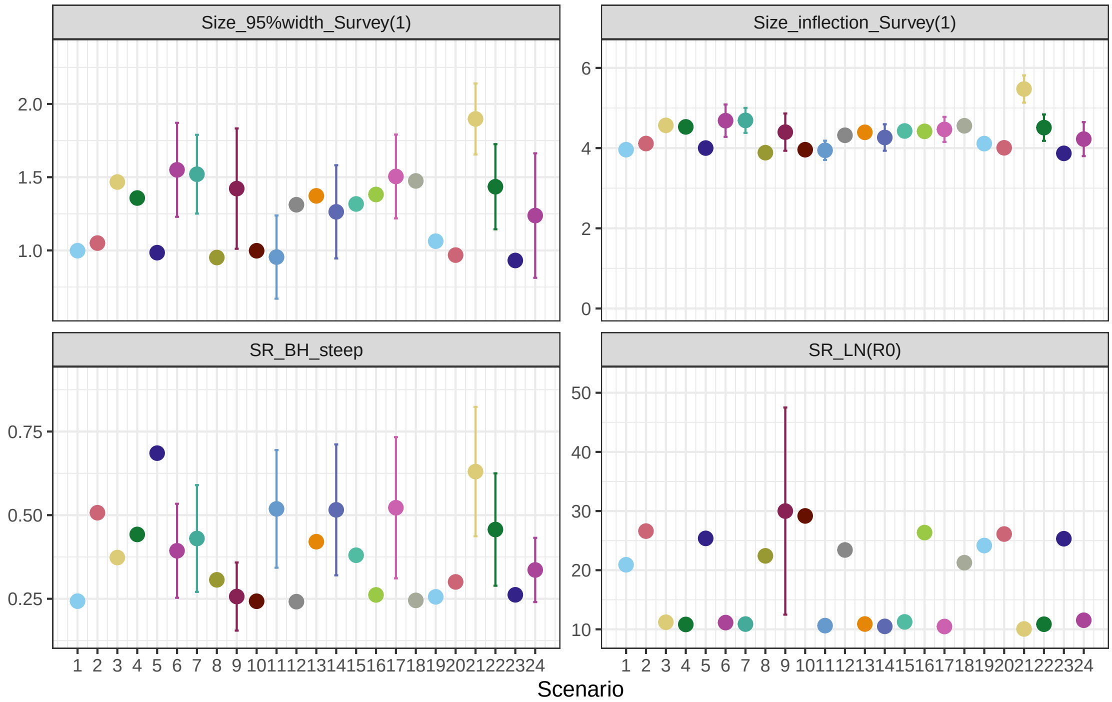


Figure F.44: Parameter estimates for all 24 monthly mud bug Stock Synthesis models

F.8 Discussion

The results reported here are the first attempt to assess stocks of sand and mud bugs using Stock Synthesis in Queensland, Australia. The results presented within this section of the report were not previously presented to the project team. All suites of Stock Synthesis models (i.e., 25 annual sand bug scenarios, 24 annual mud bug scenarios, 25 monthly sand bug scenarios and 24 monthly mud bug scenarios) failed to pass model validation. Therefore, no base case was selected from the suite of Stock Synthesis models. Nevertheless, the results of Stock Synthesis modelling are presented herein for transparency.

This discussion will focus on equivalent models to DDUST where split catch rates, 100% harvest and medium levels of natural mortality were input for both annual and monthly time steps. Biomass estimates for annual sand and mud bug models (with split catch rates, 100% harvest and medium natural mortality) were 42% and 79% of unfished biomass, respectively. Biomass estimates for monthly sand and mud bug models (with split catch rates, 100% harvest and medium natural mortality) were 47% and 123% of unfished biomass, respectively.

F.8.1 Performance of the population model

Sand and mud bug population models were configured as two-sex models for both annual and monthly time steps within the framework of Stock Synthesis. Sensitivity tests were constructed using 24 scenarios per suite of models to examine the robustness and performance of the model. The scenarios included changes in some crucial parameters and data inputs (see Table F.6). None of the suite of annual or monthly Stock Synthesis models were deemed adequate to asses the sand or mud bug stock for the east coast of Queensland for reasons listed below:

- For both the annual and monthly Stock Synthesis models, estimates of steepness for sand and mud bugs were erroneous. Estimates of steepness would either hit lower bounds (0.2), upper bounds (1) or have extremely wide standard deviations that exceeded the bounds, indicating low confidence in the value. It is possible that insufficient information exists in the data sets to be able to estimate steepness, and that stable models could be obtained by fixing it, however this does not resolve the issue of what value or range of values to consider.
- Fits to input catch rates tended to be over fit, with the model unable to estimate if additional catch rate standard error was required.
- Seasonal recruitment was estimated for the monthly Stock Synthesis models. 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 increased to twenty 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.
- Monthly Stock Synthesis models took up to one hour to converge, or would 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.

F.9 Unmodelled influences

See environmental and climatic influences in Section 4.3.

F.10 Recommendations

F.10.1 Research and monitoring

Research and monitoring recommendations for sand and mud bugs should focus on prioritising the reduction in model uncertainty and the rectification of caveats. In addition to the research and monitoring recommendations mentioned in Section 4.4.1, further recommendations for Stock Synthesis modelling are given below:

- **Selectivity:** For sand bugs, two main trawl gear types are used, prawn and scallop gear. Scallop gear is typically constructed of a larger mesh of approximately 4 inches (100 mm) whilst prawn gear has a smaller mesh size of approximately 2.5 inches (62.5 mm). Size-based selectivity of prawn trawl gear was estimable for sand and mud bugs from the DAF FM scallop surveys and FRDC surveys which used prawn trawl gear. The DAF FM scallop survey aimed to target both adult and juvenile saucer scallops (*Ylistrum balloti*) and required the small net mesh size of prawn trawl gear. Consequently, no available data on the size selectivity of Moreton Bay bugs is available for the larger net mesh scallop trawl gear. This is a key area of uncertainty in the Stock Synthesis modelling of sand bugs.
- **Age data:** It remains unclear what factors were preventing the Stock Synthesis models from converging. However, given Stock Synthesis is an age-based model, age data for sand and mud bugs may provide more of a basis for model calculations. In the current Stock Synthesis modelling, length frequencies from surveys such as the DAF FM scallop survey were converted to age through an input growth curve. For both sand and mud bugs, similar sized animals could belong to several age classes. Therefore, the use of length to predict age may '''smear' the assignment

of individuals to their correct age cohorts, where tracking the numbers in each cohort underpins Stock Synthesis' estimations. Determining age data from crustaceans such as crabs, prawns, and bugs has proven challenging given crustaceans must molt to grow (Hartnoll 1978; Hartnoll 2001). Recent developments in the field of DNA methylation may in the future provide a means of age determination for crustaceans (see Fairfield et al. 2021).

- **Length data:** Stock Synthesis may gain further benefit from more frequent collection of length frequency data. With the current DAF FM scallop survey design, length frequency data for sand and mud bugs is collected from a single month (generally October) of the year. As mentioned, the biology and population dynamics of Moreton Bay bugs likely occurs on a monthly time scale (i.e., spawning and recruitment). Length frequency data on a monthly time scale would provide additional recruitment information to the model when pulses of juvenile Moreton Bay bugs occur in the fishery. Concerns were raised over the larger than expected size of selectivity for sand bugs in prawn trawl gear. Perhaps, given recruitment should occur earlier in the year, smaller juvenile Moreton Bay bugs may not be present in the population in October when the DAF FM scallop survey occurs. This lack of juvenile recruits in the estimation of selectivity may lead to falsely high selectivity estimates. Future work should aim to investigate how sand and mud bug length frequencies vary throughout the year.

  Length frequency data were limited for mud bugs. The DAF FM scallop survey is conducted in the southern portion of the fishery and few mud bugs are encountered. More surveys should be conducted in the Townsville region or further north to increase the sample size for mud bug length frequency data.

F.10.2 Assessment

In addition to the assessment recommendations mentioned in Section 4.4.2, further recommendations for Stock Synthesis modelling are given below:

- **Seasonal selectivity:** Future work should aim to incorporate monthly catchability into Stock Synthesis models as per the DDUST model. Monthly patterns of catchability were reported for both sand and mud bugs from the DDUST models. This could be implemented by assigning a fleet structure where each gear type (i.e., prawn fleet and scallop fleet) is comprised of twelve fleets to represent each of the months (i.e., January, February, etc).
- **Seasonal recruitment:** As with many crustaceans, Moreton Bay bugs are relatively short-lived (max age approximately 7 years). Consequently, much of their biology and population dynamics likely occur on a monthly time scale (i.e., spawning and recruitment). Jones (1988) reported berried female sand and mud bugs to occur for approximately 8 and 7 months of the year, respectively. Stock Synthesis can be configured to distribute recruitment throughout the year, termed seasonal recruitment. For the current assessment, seasonal recruitment was estimated for both the sand and mud bug monthly models. 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, parameter bounds were twenty times that of the recommended values from the Stock Synthesis User Manual. The requirement for parameter bounds twenty times the recommended values formed part of the weight of evidence to not present the monthly Stock Synthesis models to the project team.