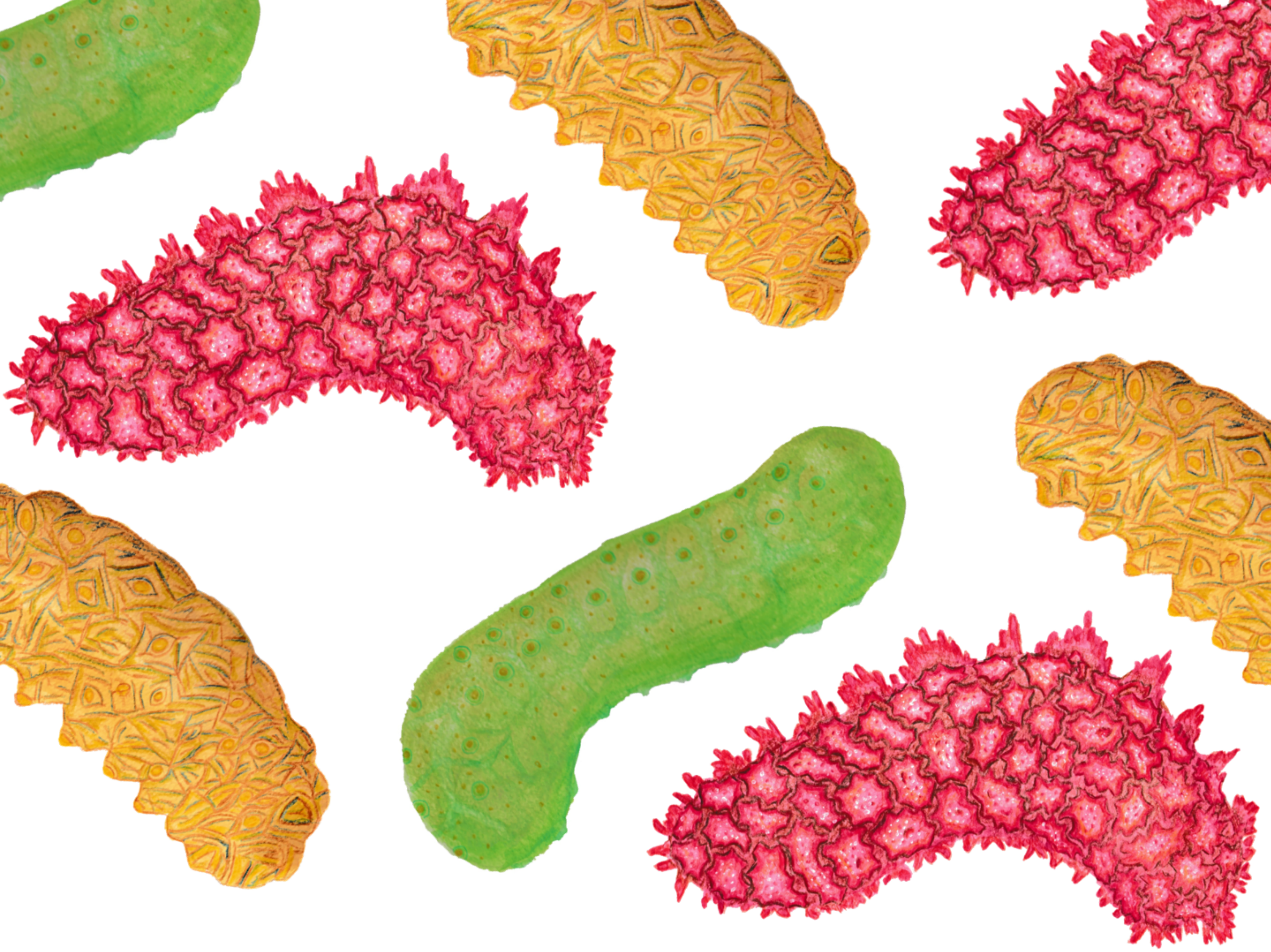

Stock assessment of Queensland east coast prickly redfish (*Thelenota ananas*), herrmanni curryfish (*Stichopus herrmanni*) and vastus curryfish (*Stichopus vastus*) with data to December 2023

May 2024

Queensland Government

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Summary

This stock assessment considered three species of sea cucumber: prickly redfish (*Thelenota ananas*), herrmanni curryfish (*Stichopus herrmanni*), and vastus curryfish (*Stichopus vastus*). Results suggest that biomass declined from an assumed unfished state in 1995 to between 73 and 116% at the end of 2023 for prickly redfish, from an assumed unfished state in 2007 to between 81 and 141% at the end of 2023 for herrmanni curryfish, and from an assumed unfished state in 2007 to between 65 and 124% at the end of 2023 for vastus curryfish.

Prickly redfish, herrmanni curryfish and vastus curryfish are species of sea cucumber from the family Stichopodidae. All three species have a broad Indo-Pacific distribution and are found in multiple countries with coral reef ecosystems. All three species occur across the Great Barrier Reef but at varying depth ranges: 10-30 m for prickly redfish, 0-25 m for herrmanni curryfish and 0-8 m for vastus curryfish.

This is the first stock assessment conducted on Queensland east coast prickly redfish, herrmanni curryfish and vastus curryfish by Fisheries Queensland.

This stock assessment includes input data through to December 2023. All assessment inputs and outputs were referenced on a calendar year basis (that is, 2023 means January 2023–December 2023).

This assessment used a one-sex age-structured population model and a delay-difference model which led to similar results. The outputs of the age-structured model are presented as the main results for all three species in this assessment.

The assessment incorporated commercial catch and effort data spanning 1995 to 2023 as well as length composition data and estimates of absolute abundance from recent surveys undertaken in 2023. No recreational or Indigenous catch data were available and catches from these sectors are considered negligible. There are no discards due to the highly selective nature of the fishery.

Retained catch estimates in live weight were used in the stock assessment models, while catch statistics are reported in salted weight for consistency with fishery reporting and management. Over the last 5 years, 2019 to 2023, prickly redfish total retained catch averaged 82 tonnes per year (39 tonnes salted weight) (Figure 1), herrmanni curryfish total retained catch averaged 76 tonnes per year (36 tonnes salted weight) (Figure 2), and vastus curryfish total retained catch averaged 28 tonnes per year (18 tonnes salted weight) (Figure 3).

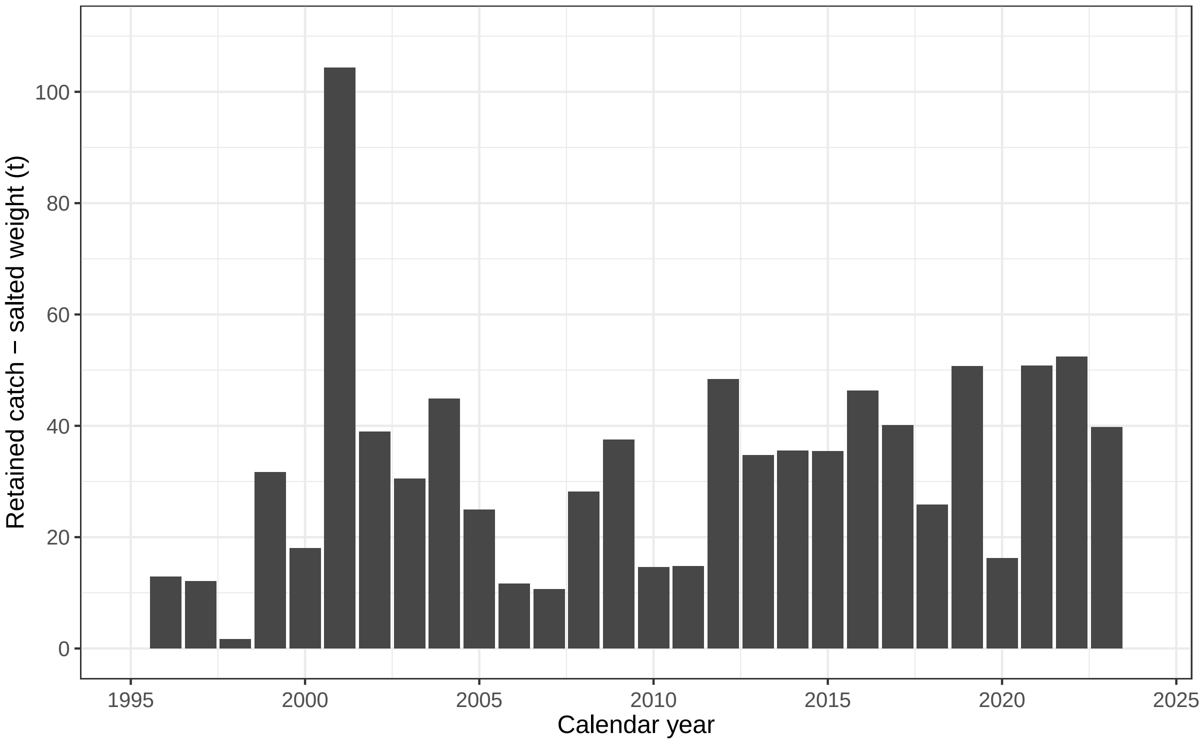


Figure 1: Annual estimated commercial retained catch between 1995 and 2023 for prickly redfish in salted weight. Catches from other sectors are not available but are considered negligible.

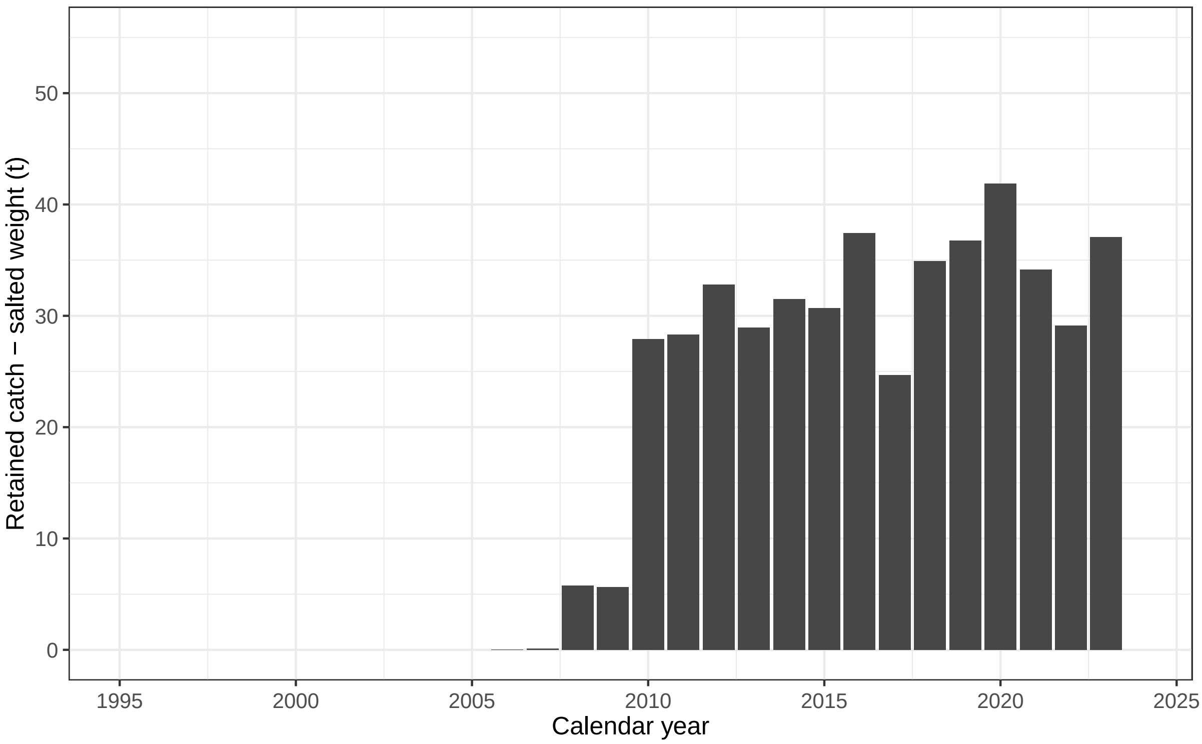


Figure 2: Annual estimated commercial retained catch between 1995 and 2023 for herrmanni curryfish in salted weight. Catches from other sectors are not available but are considered negligible.

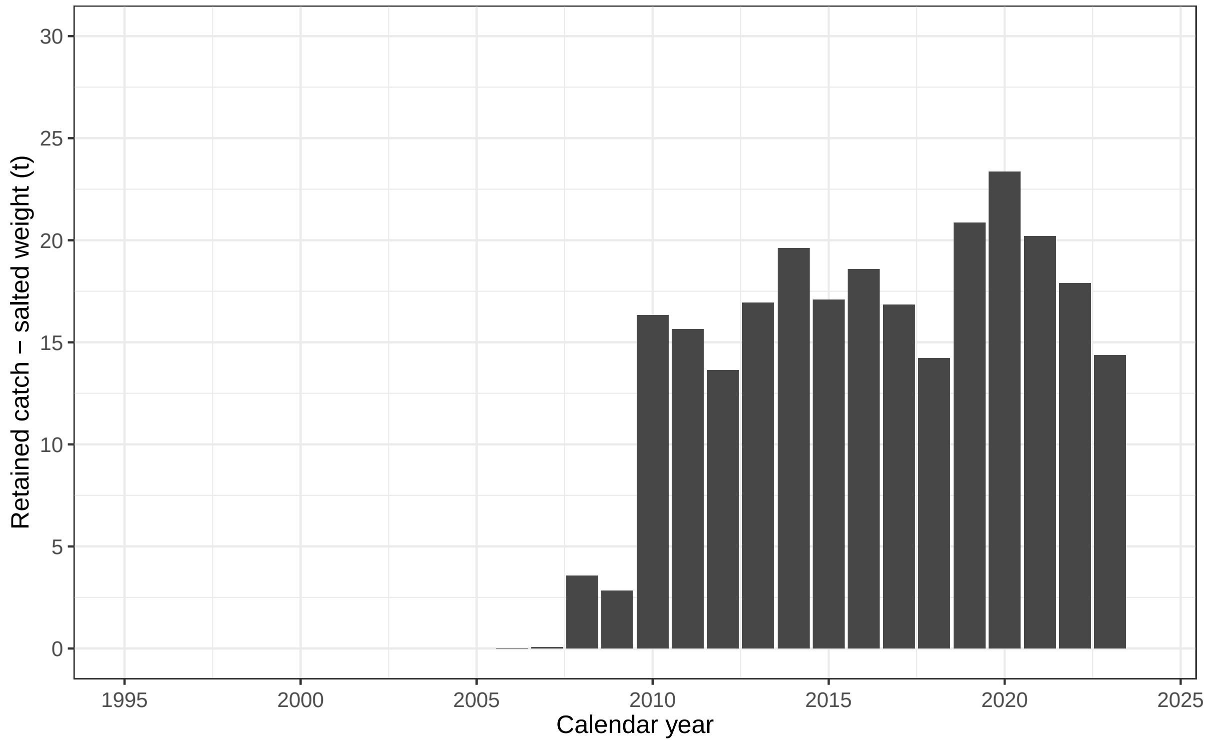


Figure 3: Annual estimated commercial retained catch between 1995 and 2023 for vastus curryfish in salted weight. Catches from other sectors are not available but are considered negligible.

Commercial catch rates were standardised to estimate an index of abundance through time (Figure 4, Figure 5 and Figure 6). The unit of standardisation was kilograms (live weight) of sea cucumber per "operation-hour", defined to be a single hour of fishing by a fisher. Year, month, grid, percentage species catch composition and vessel were included as explanatory terms.

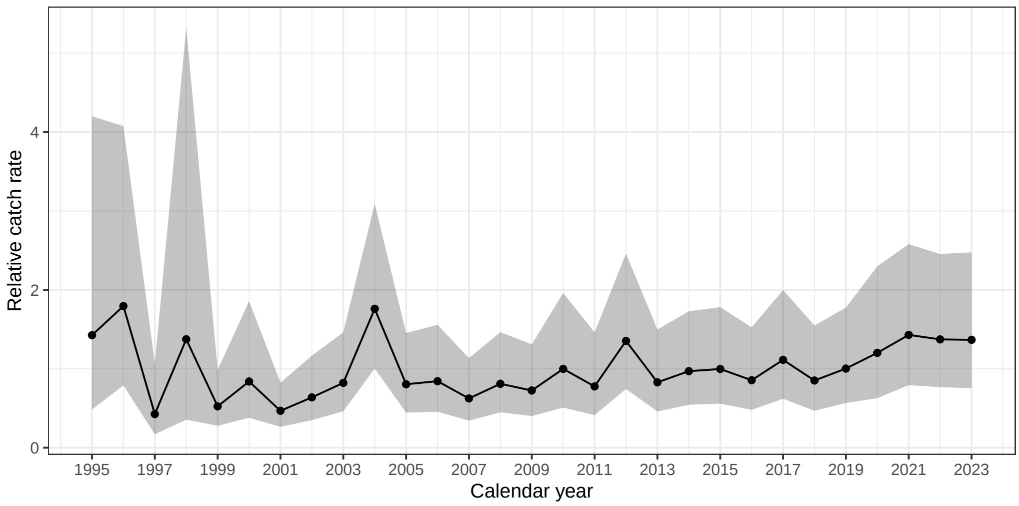
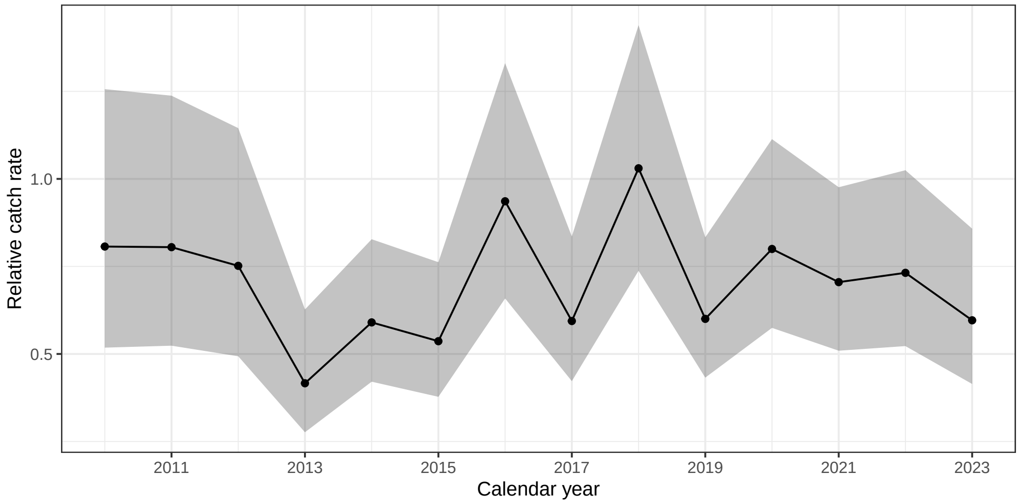


Figure 4: Annual standardised catch rates relative to average kg per hour (live weight) for prickly redfish between 1995 and 2023 .



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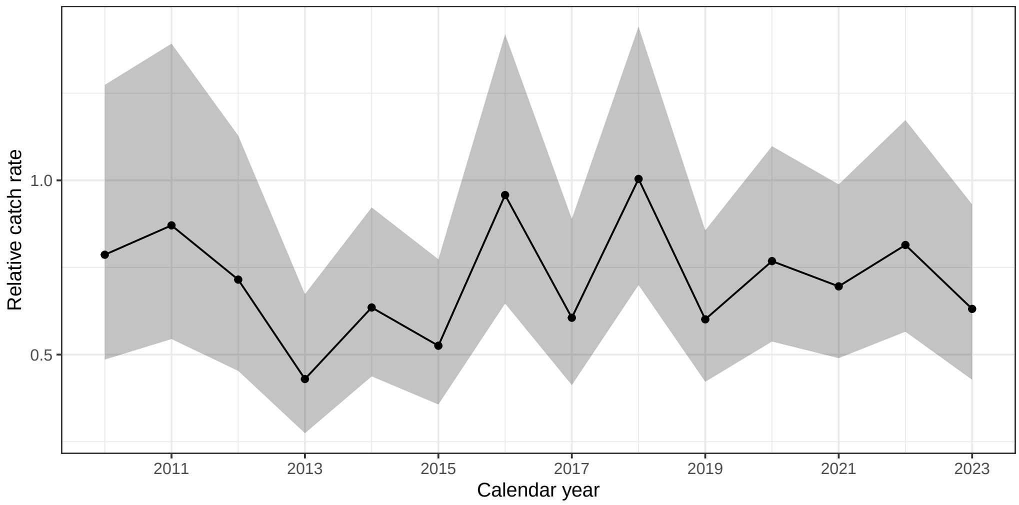
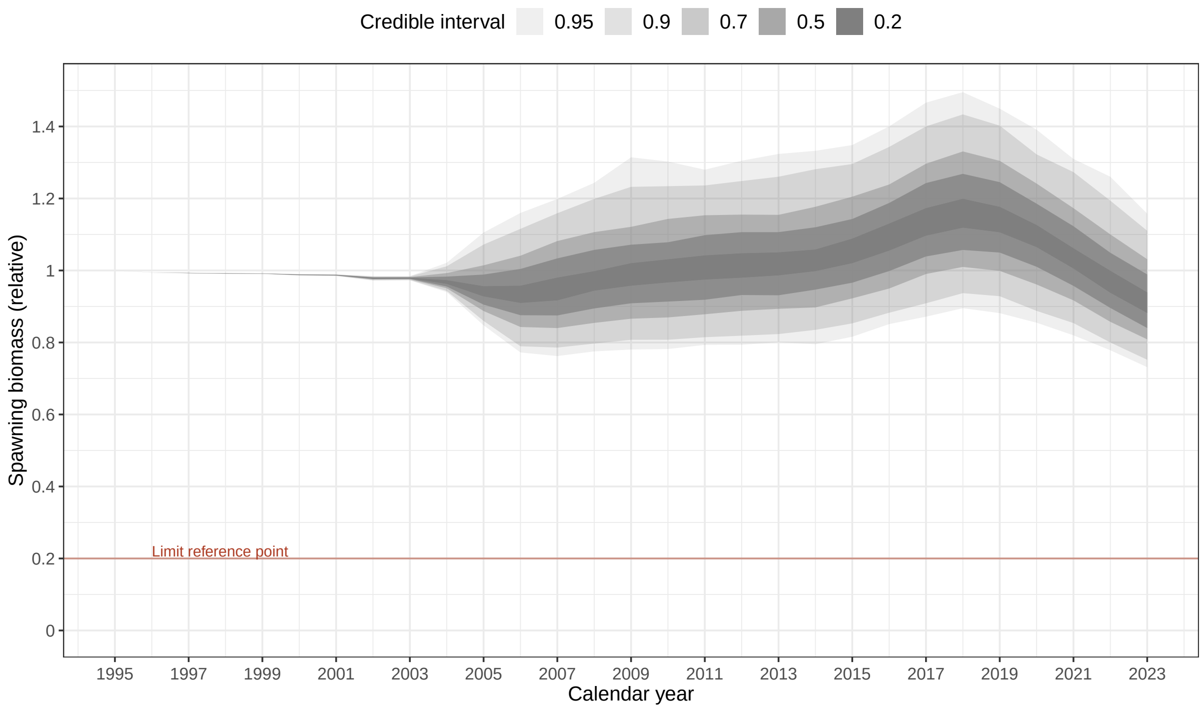


Figure 6: Annual standardised catch rates relative to average kg per hour (live weight) for vastus curryfish between 2010 and 2023 .

Up to nineteen Stock Synthesis scenarios for each species were run to examine the implications of different fixed model parameters such as steepness (*h*) and natural mortality (*M*) on model outcomes. All scenarios were optimised using Markov chain Monte Carlo (MCMC) to better explore the robustness of the models.

The base case Stock Synthesis results indicated that prickly redfish had a stable population, close to unfished levels of biomass for most of its exploitation history. The base case model indicated that the population increased to approximately 115% of unfished biomass in 2017 before decreasing to 91% of unfished biomass (73–116% range across the 95 percent credible interval) in 2023 (Figure 7 and Figure 8). Herrmanni curryfish experienced a decline from the period 1995 to 2013 to reach 86% of unfished biomass. However, the population has increased since then and in 2023 the stock level was estimated to be 103% of unfished biomass (81–141% range across the 95 percent credible interval) (Figure 9 and Figure 10). Vastus curryfish has also remained close to unfished levels for most of its exploitation history with slight declines in recent years reducing its relative biomass to 87% of unfished biomass (65–124% range across the 95 percent credible interval) in 2023 (Figure 11 and Figure 12).



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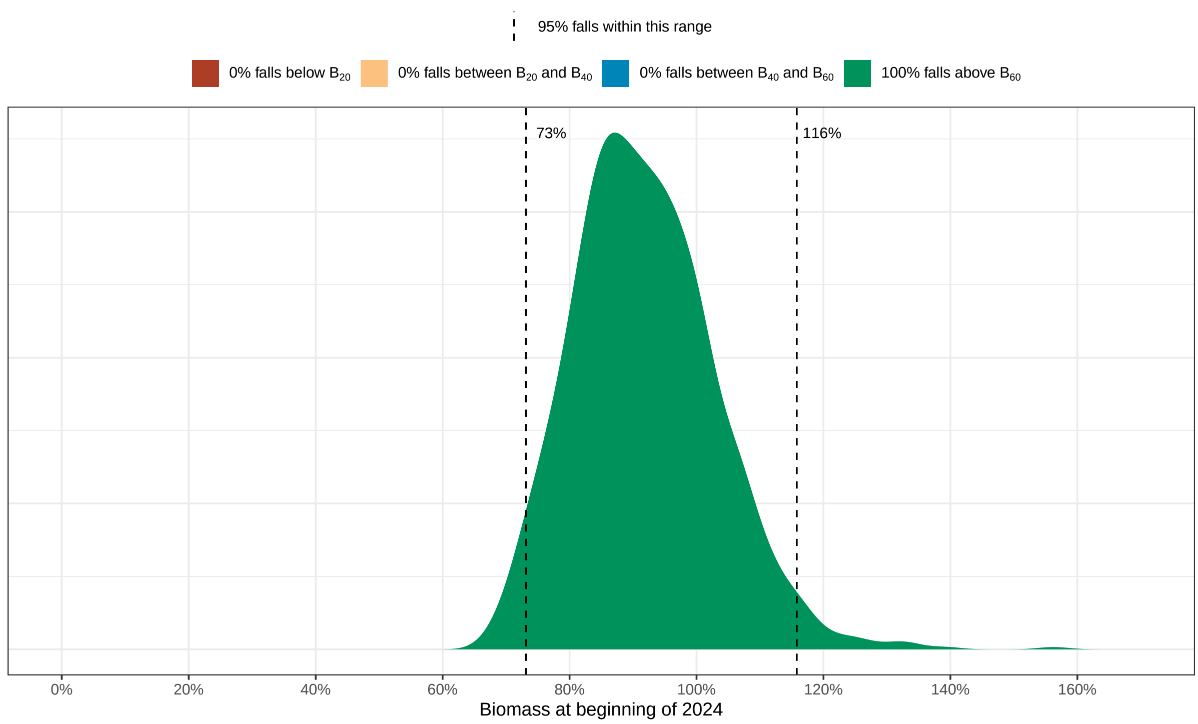

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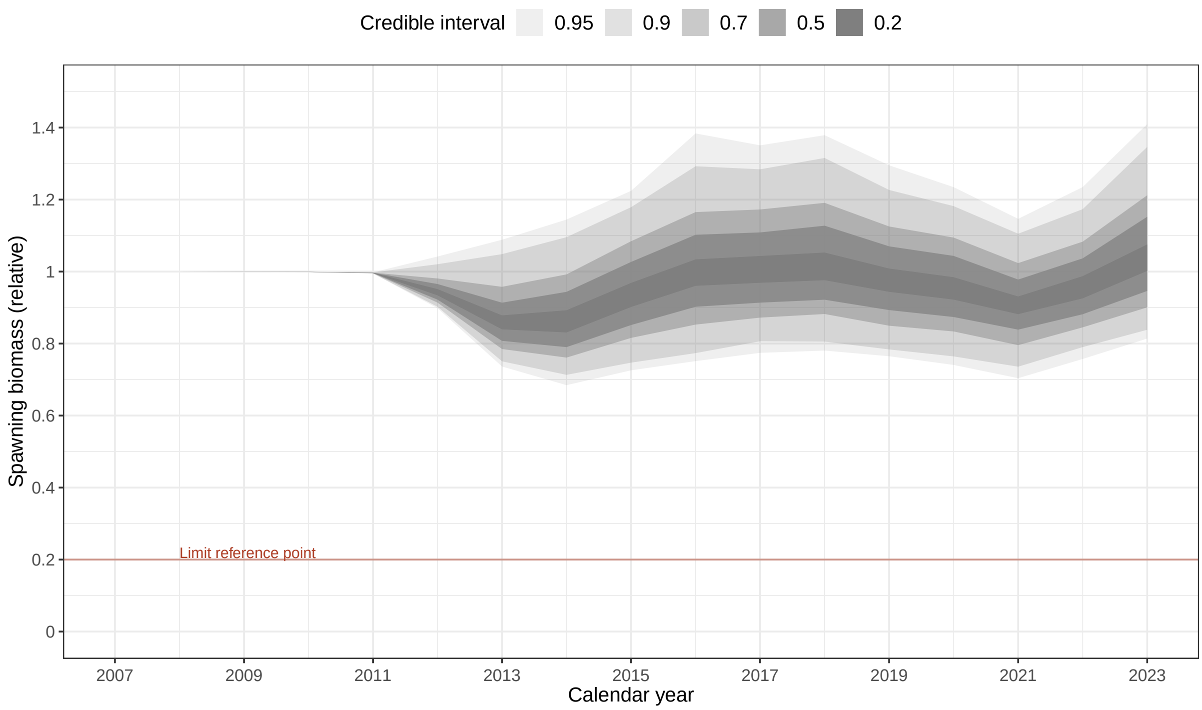


Figure 9: Estimated biomass trajectory relative to unfished from the herrmanni curryfish base case, from 2007 to 2023.

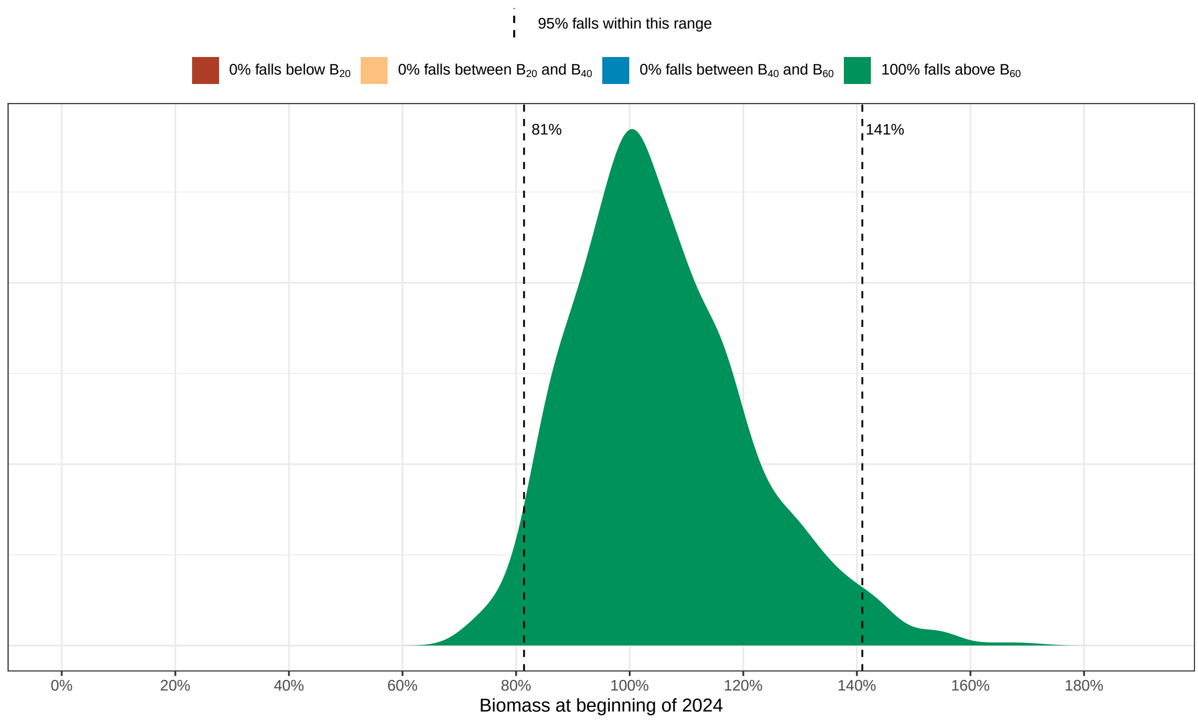
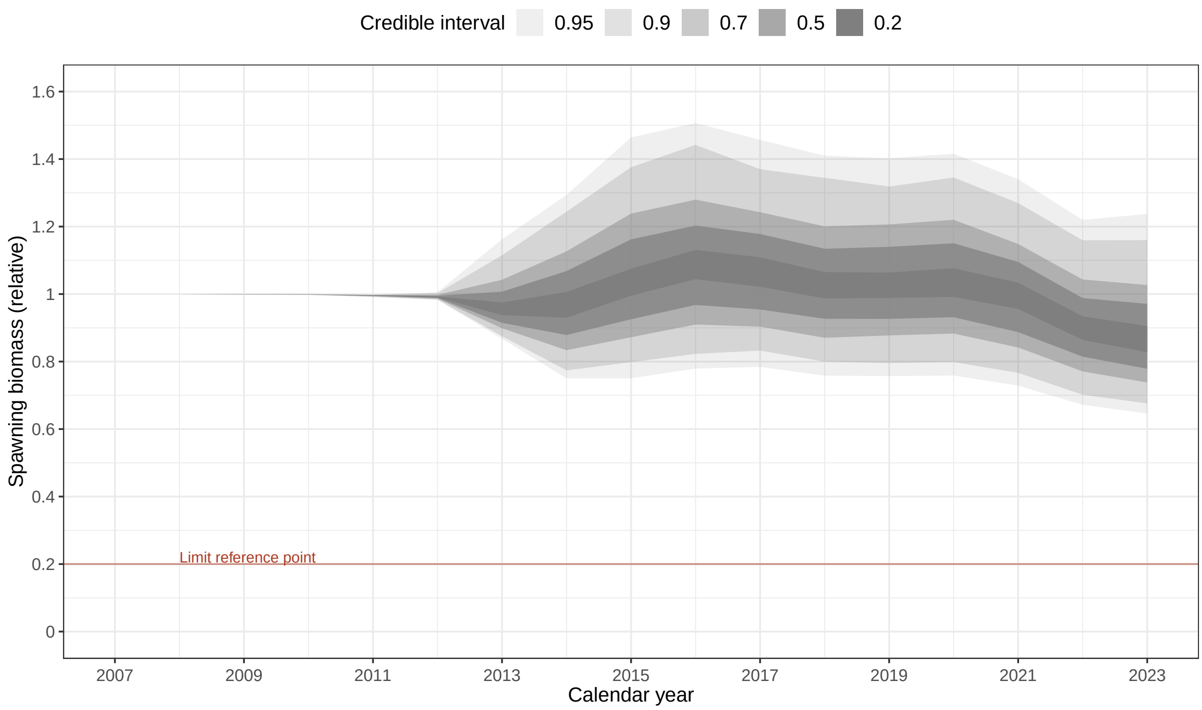


Figure 10: Probability distribution of the biomass ratio in 2023 for the base case Stock Synthesis model for hermanni curryfish with the credible interval and probability of biomass falling into the category indicated.



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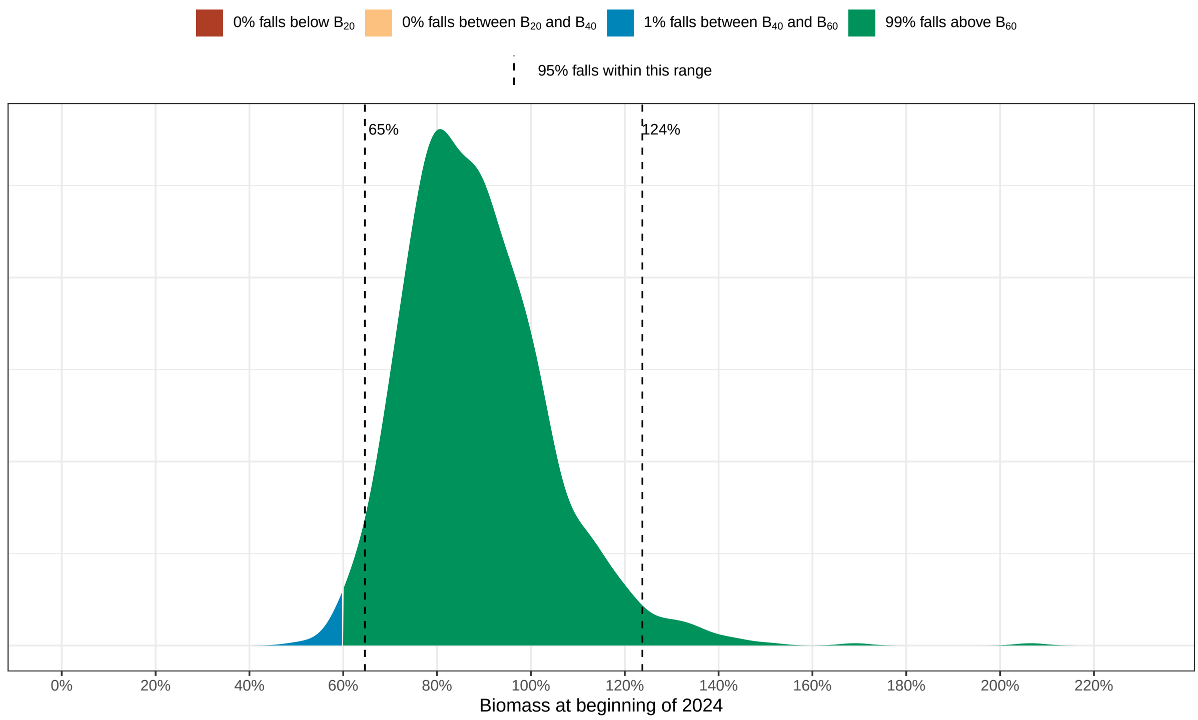

Figure 12: Probability distribution of the biomass ratio in 2023 for the base case Stock Synthesis model for vastus curryfish with the credible interval and probability of biomass falling into the two categories indicated.

Table 1: Current and target indicators for Queensland east coast prickly redfish

Indicator	Value
Biomass ratio relative to unfished)	
Range (95% credible interval)	73–116%
Probability below 20%	0%
Probability between 20% and 40%	0%
Probability between 40% and 60%	0%
Probability above 60%	100%
Average five-year (2019 to 2023) retained commercial catch (boiled and frozen weight)	39 t

Table 2: Current and target indicators for Queensland east coast herrmanni curryfish

Indicator	Value
Biomass ratio relative to unfished)	
Range (95% credible interval)	81–141%
Probability below 20%	0%
Probability between 20% and 40%	0%
Probability between 40% and 60%	0%
Probability above 60%	100%
Average five-year (2019 to 2023) retained commercial catch (boiled and frozen weight)	36 t

Table 3: Current and target indicators for Queensland east coast vastus curryfish

Indicator	Value
Biomass ratio relative to unfished)	
Range (95% credible interval)	65–124%
Probability below 20%	0%
Probability between 20% and 40%	0%
Probability between 40% and 60%	1%
Probability above 60%	99%
Average five-year (2019 to 2023) retained commercial catch (boiled and frozen weight)	18 t

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This project was commissioned by the Department of Agriculture and Fisheries. Seafresh Australia Pty Ltd and Tasmanian Seafoods Pty Ltd contributed financial support.

Glossary

compulsory logbooks	the compulsory commercial logbook database managed by Fisheries Queensland
CI	credible interval
CSMP	Marion and Saumarez Reefs of the Coral Sea Marine Park
CV	coefficient of variation
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
FQ	Fisheries Queensland
GBR	Great Barrier Reef
GBRMP	Great Barrier Reef Marine Park
GLM	generalised linear model
h	Steepness parameter of the beverton and holt stock recruitment relationship
harvest	see ‘retained catch’
legal-size biomass	the total weight of fish in a population susceptible to fishing, the primary biomass measure reported by DDUST
M	Natural Mortality
MCMC	Markov chain Monte Carlo
MLE	Maximum likelihood estimate/estimation
operation-day	a single day of fishing by a primary vessel, with year, month, grid and combinations of these as explanatory terms
MLS	minimum legal size
QSCF	Queensland Sea Cucumber Fishery
RAP	Representative Areas Program
retained catch	component of the catch that is kept by fishers, also referred to as ‘harvest’ and ‘landed catch’
RHA	Rotational harvest arrangement
spawning biomass	spawning biomass, the total weight of all adult (reproductively mature) fish in a population, an indicator of the status of the stock and its reproductive capacity. The primary biomass measure reported by Stock Synthesis
SS	Stock Synthesis
TAC	Total allowable catch
TACC	Total allowable commercial catch
TMB	Template Model Builder
WTO	Wildlife Trade Organisation

1 Introduction

Prickly redfish (*Thelenota ananas*) is a species of sea cucumber from the family Stichopodidae that is found in the Red Sea, Mascarene Islands, Maldives, East Indies, North Australia, the Philippines, Indonesia, China and southern Japan, and islands of the Central Western Pacific as far east as French Polynesia (Purcell et al. 2012). In Australia, prickly redfish distributions extend along the entire Great Barrier Reef (GBR) and Marion and Saumarez Reefs of the Coral Sea Marine Park (CSMP) (Skewes 2023). Prickly redfish can occur at 10-30 m in habitats such as reef slopes and passes on hard bottom with large coral rubble and coral patches (Purcell et al. 2023).

Herrmanni curryfish (*Stichopus herrmanni*) is a species of sea cucumber from the family Stichopodidae that occurs across the Indian Ocean and is found in most countries of the western Pacific as far east as Tonga and as far south as Lord Howe Island (Purcell et al. 2012). In Australia, herrmanni curryfish distributions extend along the entire GBR. Herrmanni curryfish can occur in a wide range of shallow depths between 0 and 25 m in habitats such as seagrass beds, rubble and sandy-muddy bottoms. This species was also referred to as *Stichopus variegatus* (Conand 1993) but is now only referred to as *Stichopus herrmanni*.

Vastus curryfish (*Stichopus vastus*) is a species of sea cucumber from the family Stichopodidae that is found in Indonesia, the Philippines, Papua New Guinea, Palau Islands, Yap (Federated States of Micronesia) and northeastern Australia. Although also reported from Vanuatu, it does not appear to occur in New Caledonia (Purcell et al. 2012). In Australia, vastus curryfish distributions extend along the entire GBR. Vastus curryfish can occur in shallow depths to about 8 m in habitats such as sandy or coral rubble substrates at the base of semi-sheltered reefs.

The Queensland Sea Cucumber Fishery (QSCF) is a commercial fishery that uses hand collection, with underwater breathing apparatus to collect various sea cucumber species. The hand collection method is highly selective, resulting in minimal risk to non-target species, including parts of the Great Barrier Reef Marine Park (GBRMP). There is negligible recreational or Indigenous catches. The fishery extends from the tip of Cape York to the southern limit of Tin Can Bay. Management in Queensland applies a range of input and output controls including catch limits, vessel entry limitations, and rotational fishing that consist of spatial-yearly closures (Table 1). In 2004, a rotational harvest arrangement (RHA) was introduced in the fishery to distribute the catches spatially. The fishery area within the GBRMP and the Coral Sea are divided into 158 zones. 52 (year 1 and year 3) and 54 (year 2) zones are made available per annum and a maximum of 18 days diving is allowed per zone, per annum (Fisheries Queensland 2021). The fishery has a limited number of licences and limits to the number of divers in the water at one time. Prickly redfish in the QSCF have a minimum legal size (MLS) of 50 cm. Herrmanni curryfish and vastus curryfish in the QSCF have a MLS of 35 cm. In June 2021 prickly redfish, herrmanni curryfish and vastus curryfish were identified as Tier 2 species, with trigger catch levels applied to financial year fishing seasons. If exceeded, a competitive TACC will be set at the prescribed trigger levels: prickly redfish = 40 t, herrmanni curryfish = 50 t and vastus curryfish = 25 t.

Herrmanni curryfish and vastus curryfish are two closely related species with similar appearances that co-occur across the GBR. These species degrade quickly after capture and catches must be processed promptly in order to maintain product quality. Catches of both species are often combined to speed up their processing and avoid spoiled product. Consequently, the quality of logbook reporting varies over time and includes a period where no separation of these species occurred, followed by a period where species level reporting was either estimated or split according to a predetermined ratio.

Since 2009, prickly redfish, herrmanni curryfish and vastus curryfish have accounted for 79% of the catch of Tier 2 species, with an annual average catch of approximately 106 t. Prickly redfish, herrmanni curryfish and vastus curryfish constitute approximately 27% of total fishery catch.

Table 1.1: Management changes applied to prickly redfish, herrmanni curryfish and vastus curryfish in the Queensland Sea Cucumber Fishery

Year	Fisheries management, regulations and operations
1988	Compulsory commercial catch logbook reporting commenced
1991	Introduction of quota
1995	Introduction of logbook version BD01; number and weight required
1997–1998	Total allowable commercial catch (TACC) of 500 t for all sea cucumber species
July 2000	Introduction of logbook version BD02; reports numbers of sea cucumbers
2004	Rotational Zoning plan introduced (now Rotational Harvest Arrangement (RHA)), effort managed by a Vessel Monitoring System but not recorded in logbook until 2009 RAP 1 July: Representative Areas Program (RAP) introduced, comprehensive rezoning of the whole Great Barrier Reef protecting a total of 33% of the fishable habitat in the GBRMP
July 2006	Introduction of logbook version BD03; only numbers of sea cucumbers required (weights recorded on buyer return logbook).
July 2009	Fishers to report RHA zone
November 2013	Introduction of logbook version BD04, now reports weights instead of number of sea cucumbers
June 2021	Queensland sea cucumber fishery harvest strategy: 2021–2026 released Prickly redfish, herrmanni curryfish and vastus curryfish identified as Tier 2 species Catch trigger levels applied to financial year fishing seasons. If exceeded a competitive TACC will be set at the prescribed trigger levels: prickly redfish = 40 t, herrmanni curryfish = 50 t or vastus curryfish = 25 t
September 2021	Introduction of logbook version BD05 Commercial Logbook implemented to report estimated weights and number of containers
June 2022	Species specific reporting of curryfish required by condition 8(a) of the WTO export application

The purpose of this report is to fulfill part b) of condition 8 of the application for approval of a Wildlife Trade Operation (WTO) to export under the EPBC Act (Environment Protection and Biodiversity Conservation Act 1999 and https://www.environment.gov.au/biodiversity/wildlife-trade/commercial/operations).

Condition 8 of the WTO application states that: “The Queensland Department of Agriculture and Fisheries must:

a) Implement species-specific reporting for Curryfish for the 2022–23 fishing season and beyond.

b) Undertake and publish peer reviewed stock assessments for Prickly Redfish and Curryfish that incorporate fishery independent surveys, that are representative of the fishery, for these species by 30 May 2024.

c) The outcomes of the stock assessments must be incorporated into the updated MSE. Use information from 8a and 8b above to determine and implement the appropriate level of fishing mortality rate to be applied to these species to achieve the 60% biomass target as detailed under decision rule 3.2 of the harvest strategy for this fishery.”

Collaborative surveys between the QSCF and independent scientists were conducted in 2023 for prickly redfish, herrmanni curryfish and vastus curryfish (Koopman et al. 2024). These surveys provide an estimate of surveyed biomass and length compositions that can be used as inputs to stock assessment models. These surveys are particularly valuable as they provide estimates of absolute biomass, rather than an index to be scaled to absolute biomass. Therefore, these surveys also provide empirical information on recent harvest rates for each stock based on the estimate of biomass and corresponding catch for each species.

Many commercially exploited sea cucumber species, have had fishery expansion outpace the rate at which biological information can be produced (Friedman et al. 2011). Prickly redfish has been well studied relative to other species, with estimates of growth, maturity and mortality available from New Caledonia (Conand 1989). However, this information is much more limited for herrmanni curryfish and vastus curryfish. As a result, previous research has used values based on expert elicitation from stakeholder workshops (Skewes et al. 2014). Such information gaps have often been a barrier for stock assessments for many sea cucumber species (Purcell et al. 2013). Therefore, a key focus of this stock assessment was to develop methods that overcome the paucity of information available.

This assessment applied and compared two different stock assessment models to prickly redfish, herrmanni curryfish and vastus curryfish. These models were Stock Synthesis (an integrated age structured model) and DDUST (a delay-difference model). Both are inherently different models with different strengths and weaknesses. By applying and comparing two different stock assessment models, uncertainty that could arise from data or biological information limitations could be explored and addressed. The benefits of each of the models are:

- Delay-difference models such as DDUST require limited growth information which can be approximated from weight-length relationships, rather than length-at-age relationships. As length-at-age information is often missing for sea cucumbers. This information is often not available for sea cucumbers and delay-difference or surplus production models are commonly applied (Hart et al. 2022; Hajas et al. 2011; Hernández-Betancourt et al. 2018; Koike 2017; Ramírez-González et al. 2020; Steele et al. 2023).
- Stock Synthesis is a more comprehensive model that can consider a larger variety of data and options than most other stock assessment methods. It allows easy exploration of all the available data and provides valuable feedback and diagnostics to scientists during model development. It also provides more insight into stock dynamics and can consider selectivity and MLS, which is valuable as it makes full use of the available data.

However, corresponding trade-offs of these models are:

- As DDUST requires less information and data than Stock Synthesis, it also provides less information about the population. For example, DDUST models the legal-size biomass of the population, rather than spawning or total biomass. This is because the only information it receives is on the fished component of the population. It also cannot model selectivity nor fit to age or length structures. Therefore, the length compositions collected through recent surveys cannot be included in DDUST.
- Stock Synthesis outputs provide more information on the population but the model requires information on growth and maturity, which is not available for many sea cucumber species. Assumed parameters must therefore be used in these models, which is not ideal.

Both stock assessment models were applied to all three species using assumptions of species biology as necessary for Stock Synthesis, and (to a lesser extent) DDUST. Any assumed values were sensitivity tested to understand their effect on model outputs and performance. Several other scenarios were tested for both DDUST and Stock Synthesis. The assessment uses calendar year data (January 1 to December 31 each year) up to the end of December 2023 to provide estimates of relative biomass that support harvest control rules specified in the harvest strategy (Fisheries Queensland 2021).

2 Methods

2.1 Data sources

Data sources included in this assessment (Table 2.1) were used to determine catch rates, length compositions, biomass estimates and annual harvests. The assessment period began in 1995 up until and including 2023 based on available information.

Table 2.1: Data compiled for input into the population model

Type	Year	Source
Commercial vessel data	1995–2023	Commercial logbook data collected by Fisheries Queensland.
Commercial buyer data	2001–2023	Buyer logbook data collected by Fisheries Queensland
Fishery independent survey data for prickly redfish, herrmanni curryfish and vastus curryfish	2023	Koopman et al. (2024)

2.1.1 Regions

All three species also occur in the green zones introduced in July 2004 through the GBRMP Representative Areas Program (RAP). However, these populations could not be included in the assessment as there are little to no data available from green zones. Biomass surveys undertaken in 2023 occurred within a small number of green zones (Koopman et al. 2024). However, this information was insufficient to allow spatially structured models that incorporate the RAP to be included in this assessment. Therefore, all estimates presented are based on areas open to fishing. These estimates can be considered conservative given that they do not include protected populations occurring within zones closed to fishing that constitute 37% of the GBRMP.

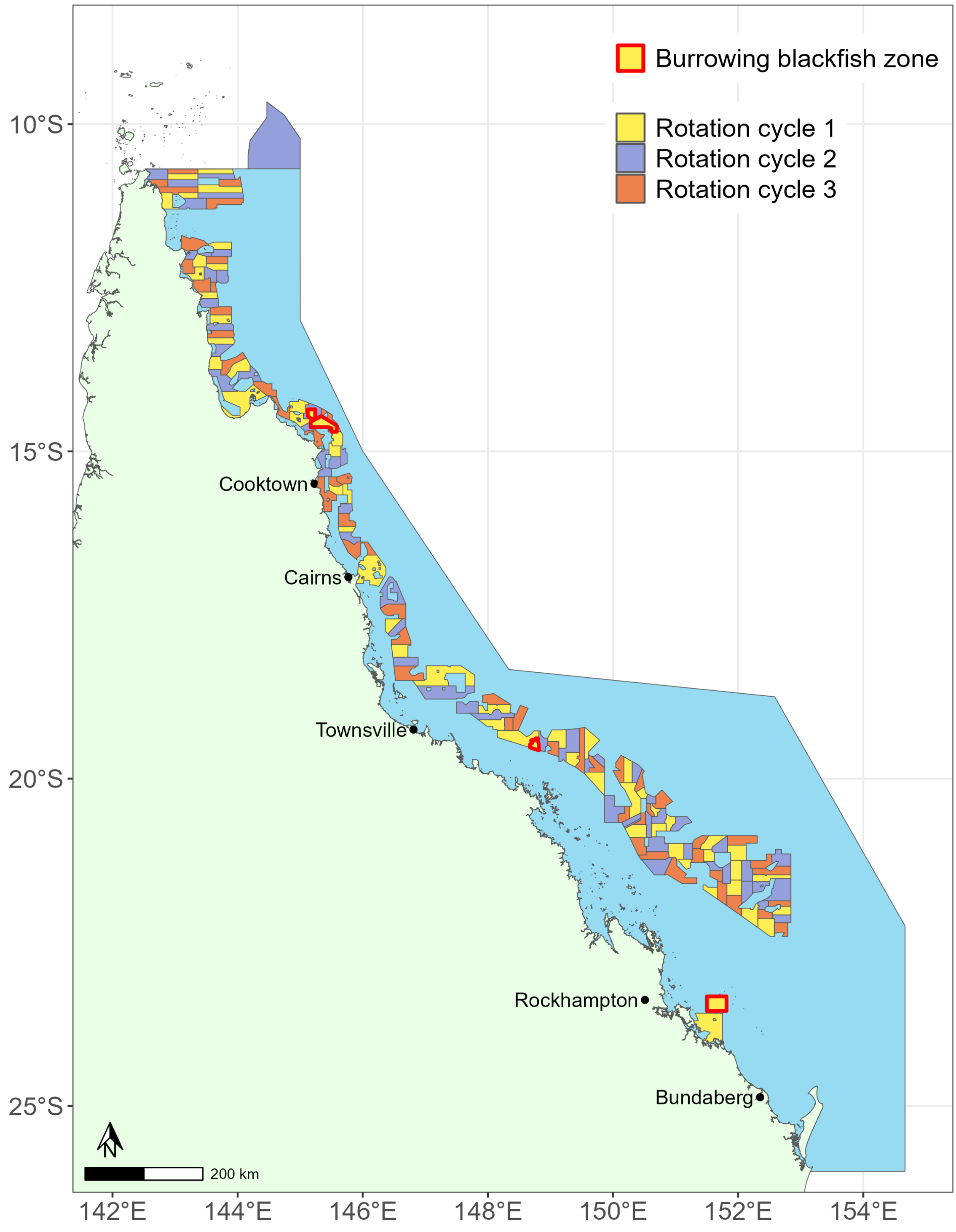

Figure 2.1: Map of the Queensland Sea Cucumber Fishery RHA zones and the locations of the burrowing blackfish zones.

2.1.2 Commercial logbook and buyer return data

Commercial catch and effort data were sourced from the Fisheries Queensland compulsory logbook records, which began in 1995. This data contained daily entries for each boat for harvest in kilograms or number of sea cucumbers (depending on reporting year), product form (salted, boiled and frozen, etc.), effort as fisher hours, RHA zone and fishing grid (Table 2.1), allowing fine scale spatial distribution of fishing effort to be determined.

Commercial catch estimates were also sourced from buyer return data that has been collected since 2001. Conventionally, buyer returns have been used when catch alone is reported for the Queensland Sea Cucumber Fishery as these estimates are considered more accurate (e.g. Pidd et al. 2021). However, catches from buyer returns are not available prior to 2001 and these records do not contain information on fishing operations such as effort and location. Reported catches could only be linked to buyer sales, rather than specific fishing events. Therefore, information on catches were reconstructed from logbooks such that harvests matched the total statewide prickly redfish, herrmanni curryfish and vastus curryfish catches reported in the buyer returns. This combines the longevity and fine scale fishing data available from logbooks with the accuracy of catches determined from buyer returns (full details are available in Section 2.2.1).

2.1.3 Fishery independent surveys

A GBR wide survey was undertaken in September 2023, providing estimates of biomass for all three species (Koopman et al. 2024). This survey used a random stratified design undertaken across key habitats to determine the density of each species for different strata (Koopman et al. 2024). These densities were then scaled to the total biomass according to the available habitat across the GBR and corresponding densities. These surveys were undertaken by independent scientists from Fishwell Consulting in collaboration with commercial fishers. Length and weight measurements were collected during the surveys and used to scale density estimates to a final biomass. This length composition data also provides information on population length structure at the time of the surveys. Estimates of survey biomass do not capture the entire population for each species within the GBR. However, these surveys were designed so they were representative of the fishery by accounting for the majority of the fishery's spatial footprint.

2.2 Harvest estimates

2.2.1 Commercial

Harvest estimates from 1995 to 2023 were reconstructed from the logbook and buyer return data. Sea cucumber fisheries conventionally report several different forms of product weight rather than live weight. The Queensland Sea Cucumber Fishery is no different with the majority of catch records for these species reported as salted weight. In recent years, almost all of the catches have been salted product as this product form corresponds with the trigger catch levels (Fisheries Queensland 2021). The logbook reporting requirements have changed through time and therefore several data cleaning steps were undertaken:

- From 2006 to 2013, logbook catches were reported in numbers rather than weights. For these records, catch in weight was calculated based on the average weight of prickly redfish, herrmanni curryfish and vastus curryfish from logbook and buyer return records where number and weight were reported.
- Logbook catches were scaled so that the total species catch matched the total catch from buyer returns for each financial year.
- Product weights (mostly salted) were scaled to live weight based on the product conversion factors from the Torres Strait Bêche-de-mer Fishery (Murphy et al. 2021).

Retained catch estimates in live weight were used in the stock assessment models, while catches statistics are reported in salted weight for consistency with fishery reporting and management.

Due to the hand harvest nature of the fishery, there are no discards nor bycatch that need to be considered in this assessment.

2.2.2 Additional curryfish data processing

Additional processing was required for herrmanni curryfish and vastus curryfish to delineate these two species when they have been co-reported. Early in the fishery's history these two species were combined in logbooks and presented as a single species (referred to here as 'undifferentiated curryfish'). From approximately 2013 onwards, species specific reporting was implemented but was often only undertaken using estimated species ratios. This was often performed as a standard 2:1 ratio of herrmanni curryfish to vastus curryfish. However, recorded ratios can differ to this, indicating fishers have attempted to estimate this ratio in those records. To account these unresolved catches in the assessment two methods were used to split herrmanni curryfish catch and vastus curryfish catch.

Method 1: logbook reported catch
Logbook catches for undifferentiated curryfish were duplicated and replaced with either herrmanni curryfish or vastus curryfish based on the curryfish ratio determined by the average proportion of total vastus curryfish catch to herrmanni curryfish catch from logbook records, which was 0.34. Therefore, 34% of undifferentiated curryfish catch was assigned to vastus curryfish and 66% of undifferentiated curryfish catch was assigned to herrmanni curryfish.

Method 2: imputed catch
Logbook reporting for curryfish has often been assigned a 2:1 split of catch for herrmanni curryfish to vastus curryfish. For catch records where this ratio was not 30-40%, then that split was retained with the assumption that an attempt had been made to estimate the species proportions. For records where the vastus curryfish to herrmanni curryfish ratio was 30-40%, the average proportion for that latitude band was assigned to vastus curryfish and herrmanni curryfish. For undefined curryfish, the average proportion for that latitude band was assigned to vastus curryfish and herrmanni curryfish.

Method 2 (henceforth"imputed catch") was considered the best approximation of curryfish catches as it makes best use of the available information and places greater value on logbook records where the species ratio is more accurate. This approach was used as the base case scenario for both DDUST and Stock Synthesis models with Method 1 (henceforth "logbook recorded catch" when referring to curryfish) included as a sensitivity analysis.

2.2.3 Recreational and charter boat

There is no information available on recreational nor charter boat catches. However, these catches are considered negligible with the recreational and charter sectors allocated a combined 1% of the statewide harvest for all sea cucumber species (Fisheries Queensland 2021).

2.2.4 Indigenous

The traditional fishing rights of Aboriginal peoples and Torres Strait Islanders are protected under native title legislation and accordingly there is no defined allocation (Fisheries Queensland 2021). However, it is assumed that large catches do not occur via traditional fishing methods given the depth that these species occur.

2.3 Standardised indices of abundance

2.3.1 Catch rates

Queensland logbook records of commercial retained catch (adjusted according to Section 2.2.1 and 2.2.2) for each species (kg live weight) per fisher per hour were used as an index of legal-sized abundance. A unit of effort of kg per fisher hour represents the entirety of a fishing event which includes search time, bottom time (i.e. active fishing while diving), a fishers surface interval and the product processing time associated with a days fishing. The catches of individual divers were not available in records, so individual fisher performance could not be evaluated. The catch rate index was standardised to remove the influence of a number of factors not related to abundance. This section outlines the standardisation procedure.

2.3.1.1 Data filtering

To produce reliable indices of abundance that avoid confounding influences on catch rates (e.g. vessel or location), the vessels and grid cells that did not substantially contribute to the fishery, or that were not representative of the fishery, were removed prior to catch rate analysis per the following filters:

- The data were reduced to boats who fished in more than two years. For example, for prickly redfish catch rate data set, the logbook data were reduced to boats who had fished for prickly redfish in more than two years.
- The data were reduced to boats who fished a total of more than 100 kg. For example, for prickly redfish catch rate data set, the logbook data were reduced to boats who had caught a total of more than 100 kg of prickly redfish over the whole logbook time period. This was to remove trivial records.
- The data for herrmanni curryfish and vastus curryfish were reduced to Hookah diving fishing methods.

2.3.1.2 Standardisation model

Annual mean catch rates were standardised using the computer software R (R Core Team 2020). Standard errors were calculated for all estimates. The importance of individual model terms was assessed formally using F statistics by dropping individual terms from the full model.

The GLM response variable consisted of the daily catch (weight) taken by each fishing-operation (boat). Explanatory model terms included main effects for the fishing years, months, boats, six minute logbook grids and the logarithm of the total hours fished was used as an offset. For the prickly redfish catch rate standardisation, *catch percent* was introduced as a variable. This was to capture targeting behaviour, where a catch percent of more than 50% would indicate that prickly redfish was the targeted species. The data could not support use of this variable for Curryfish species. The number of covariates was limited in the analysis due to the small fleet size of the fishery. For example, records in several years may occur from a single vessel in specific months, creating colinear explanatory variables. Variables were dropped as necessary when this occurred with a preference for retaining *boat* as this was determined to have the largest effect on catch rates.

The GLM for all three species used a Gamma distribution with a log-link function. The standardisation for herrmanni curryfish and vastus curryfish was performed using the imputed catch logbook data, except for the sensitivity scenario where logbook reported catch was used. Here, that catch and effort data was used in the standardisation.

The R equation form of prickly redfish GLM was:

$$\textit{weight} \sim \textit{year} + \textit{fishing method} + \textit{catch percent} + \textit{grid} + \textit{offset(ln(fisher.hours))} \tag{2.1}$$

The R equation form of herrmanni curryfish GLM was:

$$\textit{weight} \sim \textit{year} + \textit{month} + \textit{boat} + \textit{grid} + \textit{offset(ln(fisher.hours))} \tag{2.2}$$

The R equation form of vastus curryfish GLM was:

$$\textit{weight} \sim \textit{year} + \textit{month} + \textit{boat} + \textit{grid} + \textit{offset(ln(fisher.hours))} \tag{2.3}$$

where the GLM type and variables were:

- *weight*: daily catch per boat operation (weight)
- *year*: calendar year 1995 to 2023 (factor) for prickly redfish, calendar year 2010 to 2023 (factor) for herrmanni curryfish, calendar year 2010 to 2023 (factor) for vastus curryfish
- *month*: month (factor)
- *boat*: anonymous codes for different operations (factor)
- *grid*: fishing grid (factor)
- *catch percent*: percentage catch of species divided into 0–25%, 25–50%, 50–75%, 75–100% (factor)
- *offset(ln(fisher.hours))*: model offset using fishing effort on log space.

From the GLM, standardised catch rates were formed in R by using two steps. Prediction of a full interaction table was formed in step A for weight of fish (values on the scale of the linear predictions were back transformed using the link function). Secondly this table was then averaged in step B.

Step A was to calculate the full table of predictions using R's PREDICT command, classified by every factor in the GLM. The number of fisher hours used in the predictions were set at mean number of hours per day over the last five years.

Step B performed a weighted average of the full table of predictions from step A. Factors that were not specified in the predictions, were averaged by marginal weights applied to each factor level. That was, by the number of data occurrences, scaled to proportions, of each of it's factor levels in the whole dataset. This averaging is the appropriate way of combining predicted values over levels of a factor (VSN International 2022).

The resulting predictions from step B were the standardised weight of catch in weight per fisher-operation-hour. The prediction settings for the annual index of abundance by year, over steps A and B, were:

- *year*: all years predicted.
- *month*: all months predicted.
- *grid*: all grids predicted.
- *boat*: marginal weight for an average boat-operation over the last five years.
- *catch percent*: marginal weight for an average catch percent over the last five years.
- *total hours*: logged offset calculated from the average over the last five years.

2.3.2 Biomass estimates

Recent surveys provided a single estimate of biomass in live weight (tonnes (t)) for each species (Koopman et al. 2024). These estimates of biomass encompass the non-cryptic component of each stock which included individuals below the MLS, henceforth referred to as 'surveyed biomass'. Therefore, biomass estimates were treated differently for Stock Synthesis and DDUST according to how biomass estimates are defined in each model.

The surveyed biomass estimates were scaled to represent the total population size on the GBR by considering the proportion of total species catch (1995 - 2022) caught within the area surveyed (Koopman et al. 2024). These biomass scalings were further tested in sensitivity scenarios with varying degrees of conservatism.

2.3.2.1 Stock synthesis

The primary unit of biomass in Stock Synthesis is spawning biomass which is defined as the mature female component of the population. However, in this assessment spawning biomass refers to both males and females as the Stock Synthesis models were specified as single sex models. The legal-sized biomass (i.e., fishable biomass) is defined as the component of the population above the MLS. These are 50 cm, 35 cm and 35 cm for prickly redfish, herrmanni curryfish and vastus curryfish, respectively. The surveyed biomass estimates match neither of these biomass definitions, which was addressed by estimating the length selectivity for each species using the available length composition data. Estimates of survey biomass were fit to as an index of abundance, similar to catch rates, by setting the catchability coefficient (q) to 1. This effectively fit the total biomass to the surveyed biomass according to the length selectivity of the surveys.

2.3.2.2 DDUST

The unit of biomass in DDUST is legal-sized biomass. However, DDUST does not estimate selectivity and therefore requires refined biomass estimates as model inputs. Legal-sized biomass was determined from the surveyed biomass outside of the DDUST model by transforming the length composition to a weight composition using the weight-length relationship for each species (Section 2.4.1). The legal-sized biomass was calculated by multiplying the surveyed biomass by the proportion of this weight composition that was above the MLS. The coefficient of variation (CV) for the surveyed biomass was maintained for the legal-sized biomass and input to DDUST as a variance estimate.

2.4 Biological relationships

2.4.1 Weight-length relationship

The weight-length relationship was described as:

$$W_L = W_\alpha \times L^{W_\beta} \tag{2.4}$$

where W_L is average weight (kg) at total length L (cm), and W_α and W_β are the coefficients of the weight length relationships (Table 2.5.4). These parameters were estimated using data collected during the biomass surveys (Koopman et al. 2024). As limited length and weight data were available for vastus curryfish, weight-length relationship parameters for herrmanni curryfish were used for this species. This surrogate weight-length relationship provided a good visual fit to the limited vastus curryfish weight and length data that were available. The weight-length relationship parameters for each species are presented in table 2.5.4.

2.4.2 Maturity and fecundity

The probability of being mature at length L ($P(L)$) was pre-specified as:

$$P(L) = \left(1 + \exp^{-\ln(19)\left(\frac{L-L_{50}}{\Delta L}\right)}\right)^{-1} \tag{2.5}$$

where ΔL was calculated as $L_{95} - L_{50}$.

There is also no information on fecundity for these species. Therefore, fecundity was pre-specified to occur linearly with length.

The maturity parameters for each species are presented in table 2.5.4. There is no maturity information available for vastus curryfish, therefore the maturity parameters for herrmanni curryfish were used. The sensitivity of the Stock Synthesis model to this assumption was tested for vastus curryfish through alternate values (Section 2.5.6). Maturity estimates are not required by DDUST and therefore these assumed values had no impact on this model.

2.4.3 Growth

The von Bertalanffy growth curve was used to specify growth in the Stock Synthesis model:

$$L_a = L_\infty\left(1 - \exp^{-\kappa(a-a_0)}\right) \tag{2.6}$$

where L_∞ is the asymptotic length, κ is the Brody growth coefficient and a_0 is the age where length is zero.

The von Bertalanffy growth parameters are not available for herrmanni curryfish nor vastus curryfish. Therefore, these parameters were pre-specified with L_∞ as the maximum length of 55 cm and 40 cm for herrmanni curryfish and vastus curryfish, respectively (Skewes et al. 2014). The growth completion parameter κ was pre-specified as 0.3 cm and a_0 as zero for both species. The sensitivity of the Stock Synthesis model to these assumed parameters was tested through alternate values (Section 2.5.6).

von Bertalanffy estimates are not required by DDUST which instead uses a single parameter ρ to describe growth and productivity. ρ can be calculated using knowledge of weight-at-recruitment, weight-pre-recruitment and asymptotic weight:

$$\rho = 1 - \frac{w_r - w_{r-1}}{w_\infty - w_{r-1}}. \tag{2.7}$$

Weight-at-recruitment (w_r) and asymptotic weight (w_∞) were pre-specified using the weight-length relationship with the MLS and maximum length of each species, respectively. Weight-pre-recruitment (w_{r-1}) was approximated using the weight-length-relationship, which was sensitivity tested for the DDUST model to ensure its approximation did not bias the stock assessment results.

2.4.4 Length composition data

Length data were input to the Stock Synthesis model in two-cm length bins. No age data were available.

2.5 Population model

2.5.1 Stock Synthesis

A single-sex population dynamic model was fitted to the data to determine the number of sea cucumbers in each year and each age group using the software package Stock Synthesis (SS; version SS-V3.30.18.0). A full technical description of SS is given in Methot et al. (2021).

The model used two fleets: one for the commercial fishery which provided catch and an index of abundance, and one for the biomass surveys which provided an index of abundance and length composition data, but not catches.

2.5.2 DDUST

DDUST is a delay-difference population model and is ideal for fisheries that have the data to support mild complexity - described as being between surplus production models and full age-structured models - which is often the case for crustaceans and shellfish. The delay-difference model can also be extended to capture fine-scale growth, recruitment and mortality by reducing the time step between delays. The DDUST model was developed by Fisheries Queensland and its full mathematical description is presented in Appendix H.

In this assessment, catch, catch rates and biomass estimates were fit to using DDUST, which was specified to use the same population parameters as Stock Synthesis (e.g., h, M, σ_R). DDUST is a simpler model than Stock Synthesis and therefore cannot make use of data such as length compositions that can be used to estimate selectivity. However, DDUST does not require information on growth, maturity or fecundity which needed to be assumed for Stock Synthesis. The simultaneous use of Stock Synthesis and DDUST therefore provides two model options:

1. A model that makes full use of available data (Stock Synthesis).
2. A model that does not require strong assumptions on species biology (DDUST).

2.5.3 Model assumptions

The main assumptions of the Stock Synthesis and DDUST models were:

- The fishery began from an unfished state in 1995. However, this was sensitivity tested for prickly redfish.
- The instantaneous natural mortality rate does not depend on length, age, year or sex.
- Deterministic annual recruitment is a Beverton-Holt function of stock size. This was sensitivity tested using a Ricker spawning-recruitment relationship.
- Catch rates were proportional to abundance.
- There was a 50/50 sex ratio.

Additional assumptions for the Stock Synthesis model were:

- The proportion of mature sea cucumbers depends on length and not age.
- The proportion of sea cucumbers vulnerable to fishing depends on length and not age.
- Growth occurs according to the von Bertalanffy growth curve.

2.5.4 Model parameters

A variety of parameters were included in both stock assessments models, with some of these fixed at pre-specified values and others estimated or mirrored. For the Stock Synthesis model, uniform priors were used unless stated otherwise. Parameter values, their treatment (pre-specified, mirrored or estimated), their description, their sources and use in either the Stock Synthesis or DDUST model are available in Table 2.5.4.

The natural logarithm of unfished recruitment ($ln(R_0)$) was estimated within both the DDUST and Stock Synthesis models.

Logistic length-based selectivity parameters were estimated in the model for the biomass surveys (Size_inflection_Survey and Size_95%width_Survey). The selectivity of the commercial fleet was mirrored on survey selectivity for lengths above the MLS as the surveys were undertaken by sea cucumber fishers and therefore the selectivity would match that of the fishery above the MLS. Lengths below the MLS had a commercial selectivity of zero. Selectivity was estimated individually for each stock. Only the inflection point of the selectivity curve (Size_inflection_Survey) was estimated for vastus curryfish as the width of this curve (Size_95%width_Survey) was correlated with other parameters. Therefore, a two stage approach to model fitting was implemented where 1) both selectivity parameters were initially estimated and 2) where Size_95%width_Survey was pre-specified to this initial estimate in the final models to remove parameter correlation. Selectivity estimation only applied to the Stock Synthesis model.

Additional variance was estimated for catch rate indices to ensure that the models achieved an optimal fit to the absolute estimates of biomass provided by the surveys. This also avoided model overfitting to catch rates that would occur in years when other data sources (such as length composition and biomass) were unavailable. The effect of this additional variance was sensitivity tested for all three species and applied to both the DDUST and Stock Synthesis models (details in Section 2.5.6).

Recruitment deviations were estimated for each species. Recruitment variation (σ_R) was pre-specified for all three species at values that prevented over-fitting to catch rate indices and maintained a relative biomass trajectory that did not unreasonably exceed the unfished level biomass. This was examined through Stock Synthesis diagnostic plots from the *r4ss* package (Taylor et al. 2021) such as the dynamic B_0 figure. Recruitment deviations improved fits to length composition data and abundance indices as annual variability in recruitment allowed for changes in the population on shorter time-scales than fishing mortality alone. Alternate values of σ_R were included in sensitivity testing (details in Section 2.5.6) and applied to both the DDUST and Stock Synthesis models.

Table 2.2: Treatment of fishery constants and biological parameters in the Stock Synthesis and DDUST models for all three species. Single pre-specified values indicate a shared value across all three species.

Parameter	Pre-specified value	Treatment	Model inclusion	Description
Fishery constants				
Start year	1995	Pre-specified	Stock Synthesis/ DDUST	Commencement of catches
End year	2023	Pre-specified	Stock Synthesis/ DDUST	Final year of data
Survey selectivity		Estimated	Stock Synthesis	Logistic length selectivity of biomass surveys
Commercial selectivity		Mirrored	Stock Synthesis	Logistic length selectivity of commercial fishery; mirrored to survey selectivity above MLS
Catch rate variance:		Estimated	Stock Synthesis/ DDUST	Additional variance estimated for catch rates (Q_extraSD in Stock Synthesis; σ_I in DDUST)
Recruitment				
R_0		Estimated	Stock Synthesis/ DDUST	Average recruitment of the unfished stock
σ_R prickly redfish herrmanni curryfish vastus curryfish	0.4 0.5 0.6	Pre-specified	Stock Synthesis/ DDUST	Variability of the rec devs around the stock recruitment relationship
h prickly redfish herrmanni curryfish vastus curryfish	0.3 0.3 0.3	Pre-specified	Stock Synthesis/ DDUST	Beverton-Holt steepness (h)
Rec devs first year prickly redfish herrmanni curryfish vastus curryfish	2003 2010 2010	Pre-specified	Stock Synthesis/ DDUST	First year to estimate recruitment deviations
Length-to-weight				

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Table 2.2 – *Continued from previous page*

Parameter	Pre-specified value	Treatment	Model inclusion	Description
W_{α} prickly redfish herrmanni curryfish vastus curryfish	0.055 0.019 0.019	Pre-specified	Stock Synthesis/ DDUST	Weight-length relationship in kg and cm (Koopman et al. 2024)
W_{β} prickly redfish herrmanni curryfish vastus curryfish	1.154 1.408 1.408	Pre-specified	Stock Synthesis/ DDUST	Weight-length relationship in kg and cm (Koopman et al. 2024)
Growth parameters				
L_{∞} prickly redfish herrmanni curryfish vastus curryfish	66.3 cm 55 cm 40 cm	Pre-specified	Stock Synthesis	Asymptotic length for von Bertalannfy growth model from Conand (1989) for prickly redfish and approximated for herrmanni curryfish
κ prickly redfish herrmanni curryfish vastus curryfish	0.2 yr^{-1} 0.3 yr^{-1} 0.3 yr^{-1}	Pre-specified	Stock Synthesis	Growth coefficient for von Bertalannfy growth model from Conand (1989) for prickly redfish and approximated for herrmanni curryfish
a_0 prickly redfish herrmanni curryfish vastus curryfish	-0.63 0 0	Pre-specified	Stock Synthesis	Growth coefficient for von Bertalannfy growth model from Conand (1989) for prickly redfish and approximated for herrmanni curryfish and vastus curryfish
Other parameters				
M prickly redfish herrmanni curryfish vastus curryfish	0.63 yr^{-1} 0.62 yr^{-1} 0.73 yr^{-1}	Pre-specified	Stock Synthesis/ DDUST	Natural mortality (Conand 1989; Skewes et al. 2014)
L_{50} prickly redfish herrmanni curryfish vastus curryfish	30 cm 27 cm 27 cm	Pre-specified	Stock Synthesis	Length-at-50%-maturity from Conand (1989) for prickly redfish and from Conand (1993) for herrmanni curryfish and approximated for vastus curryfish

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Table 2.2 – *Continued from previous page*

Parameter	Pre-specified value	Treatment	Model inclusion	Description
L_{95}				
prickly redfish	45 cm	Pre-specified	Stock Synthesis	Length-at-95%-maturity; approximated
herrmanni curryfish	32 cm			
vastus curryfish	32 cm			

2.5.5 Parameter estimation

A Markov chain Monte Carlo (MCMC) was performed on all scenarios using 10 000 iterations (2000 warm-up) and 3 chains for DDUST and 100 000 iterations (2000 warm-up) and 1 chain for Stock Synthesis to investigate the posterior parameter distributions. For DDUST, the MCMC was run using the *tmbstan* package (Monnahan et al. 2018) which enables Stan (Carpenter et al. 2017) 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 E). 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.

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 percent 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 percent of the possible realisations of error. Confusingly, both are condensed to the acronym ‘CI’ but should be distinguishable by context.

2.5.6 Sensitivity tests

As with any stock assessment model, several modeling decisions and/or assumptions must be made when insufficient information is available. The consequences of these decisions were tested through sensitivity analyses where the Stock Synthesis and DDUST models were re-run using alternative conditions. These sensitivity analyses offer transparency into these decision making processes and demonstrate the impact that they have on the final model results. Here, a number of additional model runs were undertaken to determine each model’s sensitivity to pre-specified parameters, assumptions and model inputs. The sensitivities, and notations used to denote variations for Stock Synthesis and DDUST, were as follows:

- **Steepness (*h*):** Natural-scale median of the steepness prior. As the base case steepness was pre-specified at a low level (0.3), two higher values were tested as alternatives:
  - “Mid”: 0.5

- “High”: 0.7

- **Recruitment variability (σ_R):** A lower and higher alternative to σ_R were examined to test the models sensitivity to this parameter. The base case σ_R was determined through a model tuning process that minimised over-fitting to catch rate data, and was 0.4 for prickly redfish, 0.5 for herrmanni curryfish, 0.6 for vastus curryfish. These alternative values test the sensitivity of the Stock Synthesis and DDUST models to that pre-specified value.
  - “Low”: 0.2 (prickly redfish), 0.3 (herrmanni curryfish), 0.5 (vastus curryfish)
  - “High”: 0.5 (prickly redfish), 0.6 (herrmanni curryfish), 0.7 (vastus curryfish)

- **Natural mortality (*M*):** Natural mortality was pre-specified in the models as 0.63 yr^{-1} for prickly redfish based on Conand (1989), and 0.62 yr^{-1} and 0.73 yr^{-1} for herrmanni and vastus curryfish as per the MSE undertaken by Skewes et al. (2014). Two lower values were tested as alternatives. The ’Mid’ value was selected by using the pre-specified growth parameters to estimate M using a variety of methods provided in the “Natural mortality tool” (`https://connect.fisheries.noaa.gov/natural-mortality-tool/`, Cope et al. (2022)). The ‘Mid’ value was the mid-point of those values. The ‘Low’ value was arbitrarily selected to test the models sensitivities to a lower M than could be estimated through life history correlates.
  - “Low”: 0.3 yr^{-1} (prickly redfish), 0.3 yr^{-1} (herrmanni curryfish), 0.3 yr^{-1} (vastus curryfish)
  - “Mid”: 0.55 yr^{-1} (prickly redfish), 0.5 yr^{-1} (herrmanni curryfish), 0.55 yr^{-1} (vastus curryfish)

- **Catch rate variance (Q_extraSD in Stock Synthesis; σ_I in DDUST):** As noted in Section 2.5.4, additional variance was estimated for catch rates within each model, to ensure an optimum fit to biomass estimates from recent surveys. A further sensitivity test was performed where this additional variance was not applied and therefore the models could fit more freely to catch rate data.

- **Survey scale:** Survey scale was pre-specified in the models as 0.68 for prickly redfish and 0.83 for herrmanni curryfish and vastus curryfish, as per the percentage of the fishery (tonnage) encapsulated by the surveys (Koopman et al. 2024). Three values were tested as alternatives, no scaling, higher scaling and lower scaling:
  - “None”: 1
  - “low”: 0.5 (prickly redfish), 0.7 (herrmanni curryfish), 0.7 (vastus curryfish)
  - “high”: 0.75 (prickly redfish), 0.95 (herrmanni curryfish), 0.95 (vastus curryfish)

- **Catch reconstruction for curryfish (reported versus imputed logbook catches):** As noted in Section 2.2.2, two catch reconstructions were performed for herrmanni and vastus curryfish with “imputed” catch histories applied in the base case model. A sensitivity analysis included the “reported” catch histories for each of these species.
- **Growth:** As no growth information is available for herrmanni curryfish and vastus curryfish, pre-specified von Bertalanffy growth parameters were used to approximate growth (Section 2.4.3). The influence of these assumed parameters were tested by providing alternative von Bertalanffy growth parameters (L_∞ and κ) that result in faster or slower growth:
  - “Slow”(herrmanni curryfish): L_∞ = 60 cm ; κ = 0.2 yr^{-1}; a_0 = 0
  - “Fast”(herrmanni curryfish): L_∞ = 45 cm; κ = 0.4 yr^{-1}; a_0 = 0
  - “Slow”(vastus curryfish): L_∞ = 45 cm ; κ = 0.2 yr^{-1}; a_0 = 0
  - “Fast”(vastus curryfish): L_∞ = 35 cm; κ = 0.4 yr^{-1}; a_0 = 0

Similarly, the pre-specified length used to determine w_{r-1} in the ρ calculation was decreased and increased by 25% for the 'Slow' and 'Fast' growth scenarios for the DDUST model, respectively.

Additional sensitivity analyses were conducted for Stock Synthesis models on:

- **Maturity:** Similar to information on growth, no maturity information is available for vastus curryfish. Therefore, maturity was pre-specified as the maturity parameters for herrmanni curryfish (Section 2.4.2). This was further sensitivity tested by providing alternative maturity parameters (L_{50} and L_{95}) that result in earlier or later maturity:
  - "Early": L_{50} = 20 cm; L_{95} = 25 cm
  - "Late": L_{50} = 30 cm; L_{95} = 35 cm

- **Plus group age:** Stock Synthesis models include a 'plus group' where any individuals older than a specified age are aggregated into a single age class. The base-case plus group age was fixed at 13 years for prickly redfish, and 10 years for herrmanni curryfish and vastus curryfish, as per Skewes et al. (2014). This was further sensitivity tested by using an older value of 25 years for prickly redfish, and 20 years for herrmanni curryfish and vastus curryfish.

- **Shrinkage adjustment:** Length measurements collected by (Koopman et al. 2024) were taken from animals brought to the surface due to dive logistics. Therefore, there was a possibility that these sea cucumbers could have shrunk in length as a response to this. This was sensitivity tested by adjusting all individuals to 20% less than their measurement to obtain an adjusted length structure.

- **Spawner-recruitment reltionship:** The Ricker spawner-recruitment relationship was applied in place of the standard Beverton-Holt relationship:

$$R_y = \frac{R_0 SB_y}{SB_0} \exp\left[h\left(1 - \frac{SB_y}{SB_0}\right)\right] \tag{2.8}$$

  where:
  - R_0 is the unfished equilibrium recruitment
  - SB_0 is the unfished equilibrium spawning biomass (corresponding to R_0)
  - SB_y is the spawning biomass at the start of the spawning season during year y
  - h is the steepness parameter

- **Depletion:** For prickly redfish depletion in 1940 was set at 60% to test a scenario suggested by independent reviewers that this species may have been heavily exploited prior to World War II (Buckworth et al. 2024). This was not applied to herrmanni curryfish or vastus curryfish as there is no evidence that either of these species were exploited historically.

Full outputs of these sensitivity model scenarios are available in Appendices F and G. A summary of these scenarios and their numbering in Figures 3.19, 3.24 and 3.29 is summarised in Table 2.3.

Table 2.3: Scenarios tested to determine sensitivity to parameters, assumptions and model inputs

Scenario	Species	Models	Description
1	All	Stock Synthesis and DDUST	Base case
2	All	Stock Synthesis and DDUST	Mid steepness (h)
3	All	Stock Synthesis and DDUST	High steepness (h)
4	All	Stock Synthesis and DDUST	Low recruitment variability (σ_R)
5	All	Stock Synthesis and DDUST	High recruitment variability (σ_R)
6	All	Stock Synthesis and DDUST	Low natural mortality (M)
7	All	Stock Synthesis and DDUST	High natural mortality (M)
8	All	Stock Synthesis and DDUST	Extra catch rate variance
9	All	Stock Synthesis and DDUST	No survey scaling
10	All	Stock Synthesis and DDUST	Low survey scaling
11	All	Stock Synthesis and DDUST	High survey scaling
12	All	Stock Synthesis	Older plus group
13	All	Stock Synthesis	Shrinkage adjustment
14	All	Stock Synthesis	Ricker spawner-recruitment
15	H. curryfish and v. curryfish	Stock Synthesis and DDUST	Reported logbook catch
16	H. curryfish and v. curryfish	Stock Synthesis	Slower growth
17	H. curryfish and v. curryfish	Stock Synthesis	Faster growth
18	V. curryfish	Stock Synthesis	Earlier maturity
19	V. curryfish	Stock Synthesis	Later maturity
20	P. redfish	Stock Synthesis	Depletion at 60% in 1940
21	All	DDUST	Slower growth
22	All	DDUST	Faster growth

3 Results

Model inputs are described for prickly redfish, herrmanni curryfish and vastus curryfish. Outputs relate to the Scenario 1—the 'base case' (defined in Section 2.5.6) for the Stock Synthesis models. The results from the base case DDUST models are compared to the Stock Synthesis relative biomass results in Figures 3.20, 3.25 and 3.30. The complete results from the DDUST base case model are shown in Appendix C. Results for all Stock Synthesis scenarios are presented in Appendix F and all DDUST scenarios are presented in Appendix G.

3.1 Model inputs

3.1.1 Data availability

The retained catches, abundance indices (catch rates and survey), and length composition data availability are displayed for prickly redfish, herrmanni curryfish and vastus curryfish in Figures 3.1, 3.2 and 3.3.

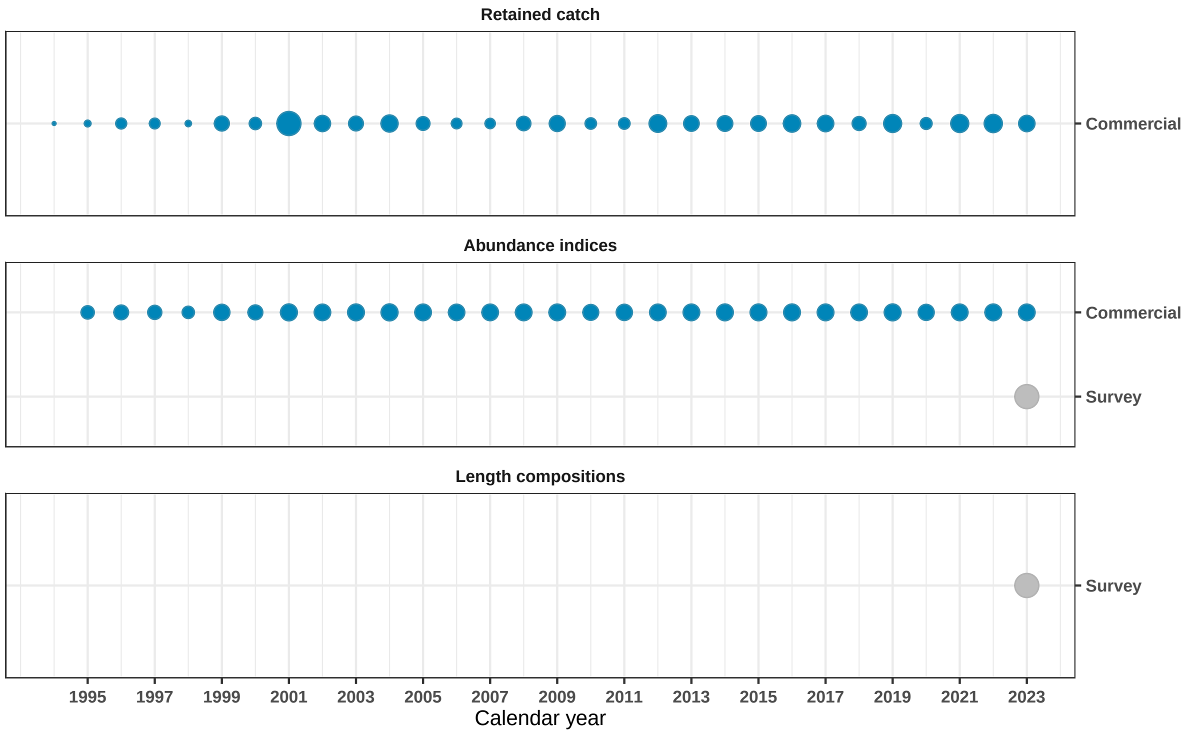

Figure 3.1: Data presence by year for each category of data type for prickly redfish.

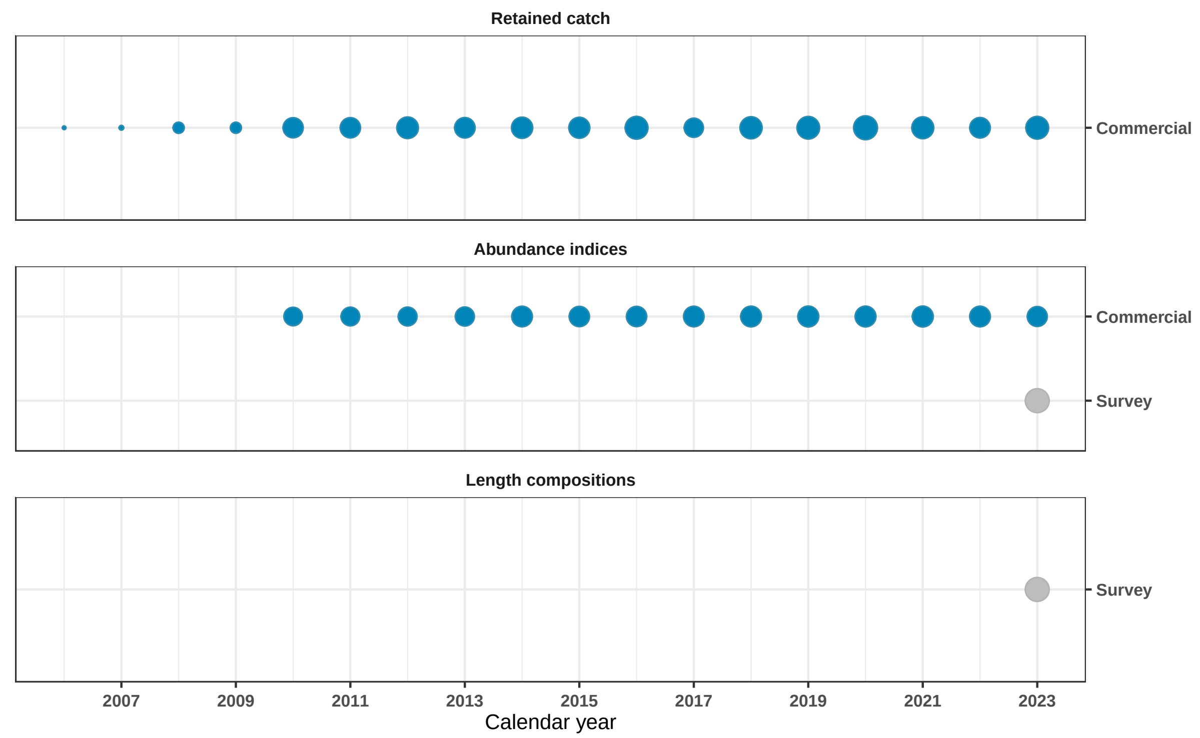

Figure 3.2: Data presence by year for each category of data type for herrmanni curryfish.

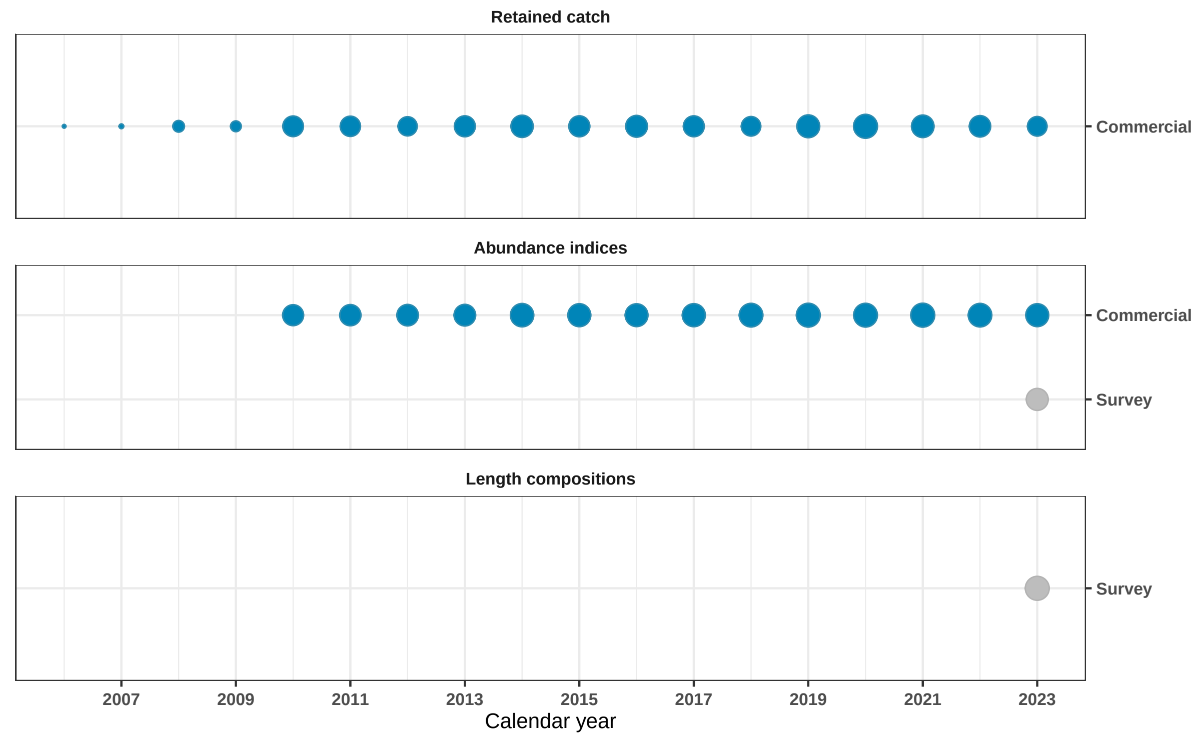

Figure 3.3: Data presence by year for each category of data type for vastus curryfish.

3.1.2 Retained catch estimates

Total annual retained catch from the commercial sector for prickly redfish is shown in Figure 3.4. The retained catch of the prickly redfish peaked in 2001 at 104 t (salted weight). Over the last 5 years (2019 to 2023) total retained catch averaged 39 t per year (salted weight). Total annual retained catch from the commercial sector for herrmanni curryfish is shown in Figure 3.5. The retained catch of herrmanni curryfish peaked in 2020 at 42 t (salted weight). Over the last 5 years (2019 to 2023) total retained catch averaged 36 t per year (salted weight). Total annual retained catch from the commercial sector for vastus curryfish is shown in Figure 3.6. The retained catch of vastus curryfish peaked in 2020 at 23 t (salted weight). Over the last 5 years (2019 to 2023) total retained catch averaged 18 t per year (salted weight).

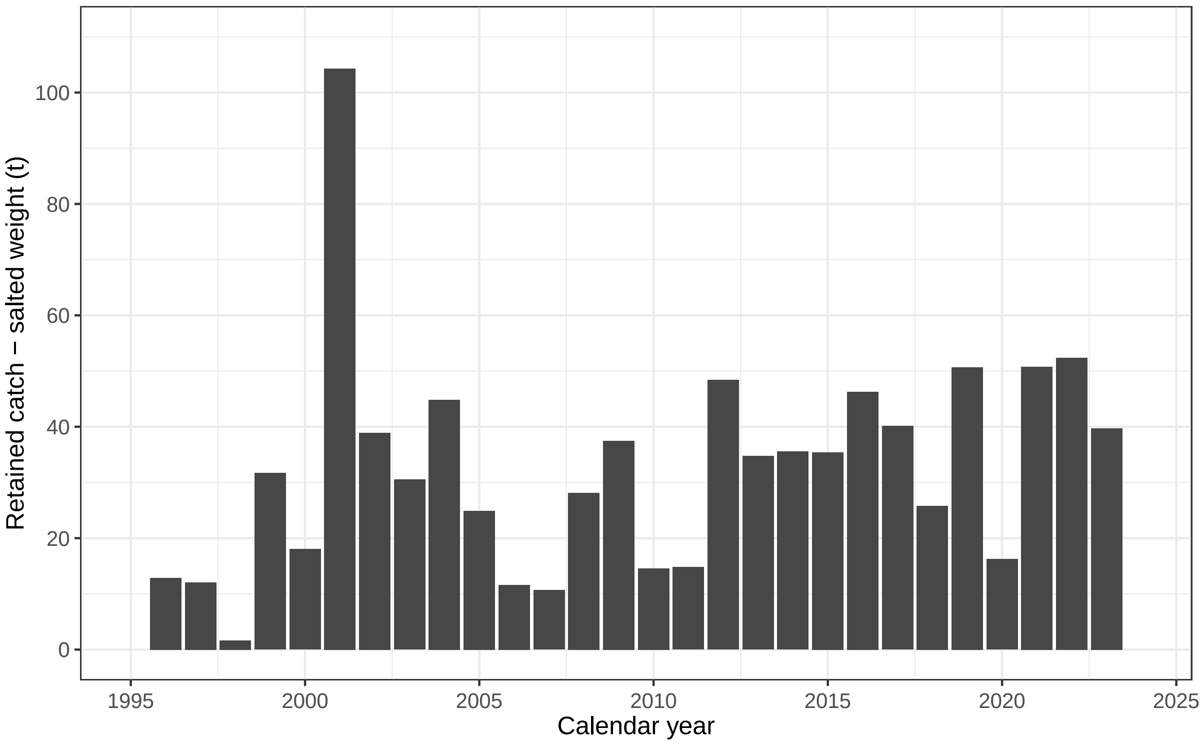

Figure 3.4: Annual estimated commercial retained catch between 1995 and 2023 for prickly redfish in salted weight. Catches from other sectors are not available but are considered negligible.

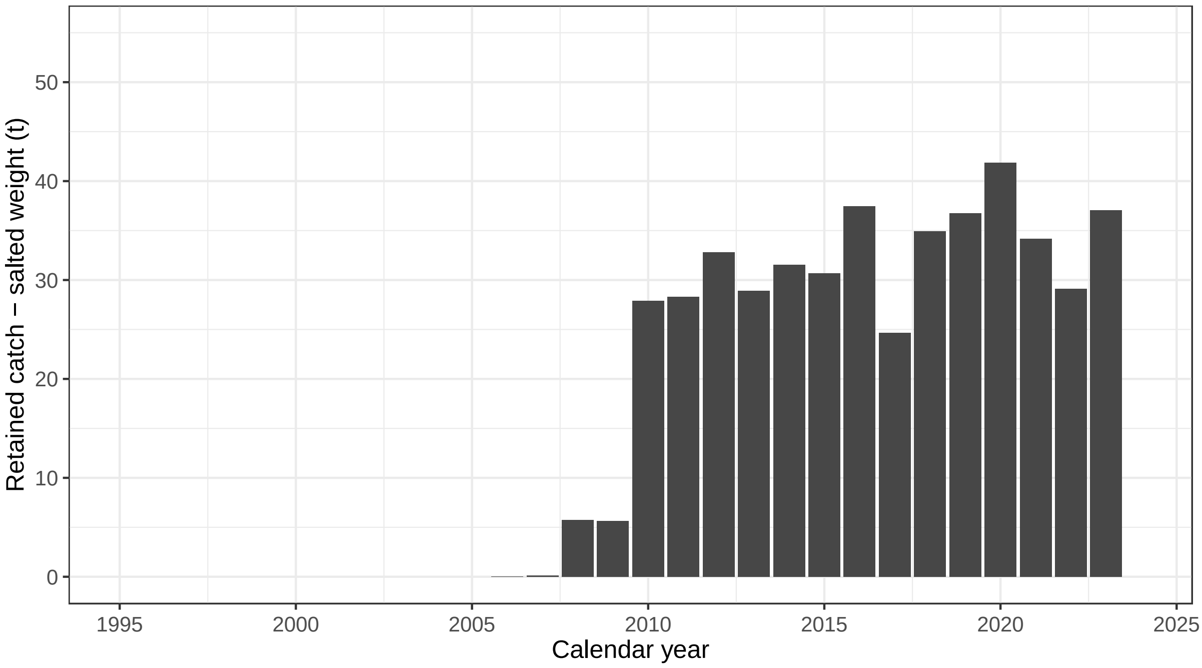

Figure 3.5: Annual estimated commercial retained catch between 1995 and 2023 for herrmanni curryfish in salted weight. Catches from other sectors are not available but are considered negligible.

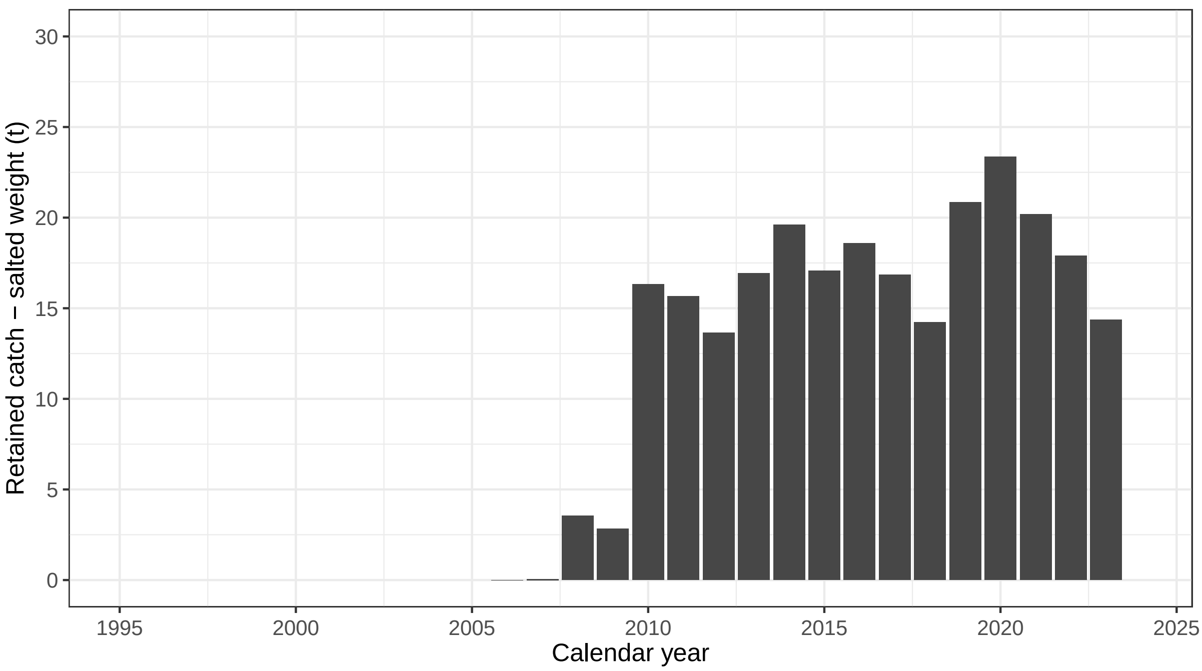

Figure 3.6: Annual estimated commercial retained catch between 1995 and 2023 for vastus curryfish in salted weight. Catches from other sectors are not available but are considered negligible.

3.1.3 Standardised catch rates

Standardised catch rates had a generally stable trend for prickly redfish and vastus curryfish with some fluctuations occurring across each time series (Figures 3.7, 3.8 and 3.9). No notable declines in catch rate have occurred for any species. Notably, catch rates had an increasing trend for prickly redfish in recent years (Figure 3.7).

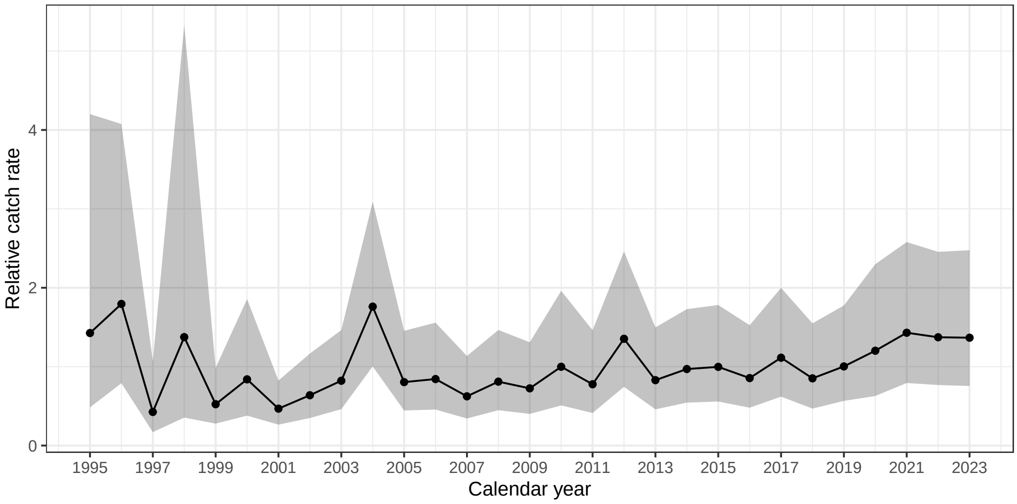

Figure 3.7: Annual standardised catch rates relative to average kg per hour (live weight) for prickly redfish between 1995 and 2023 .

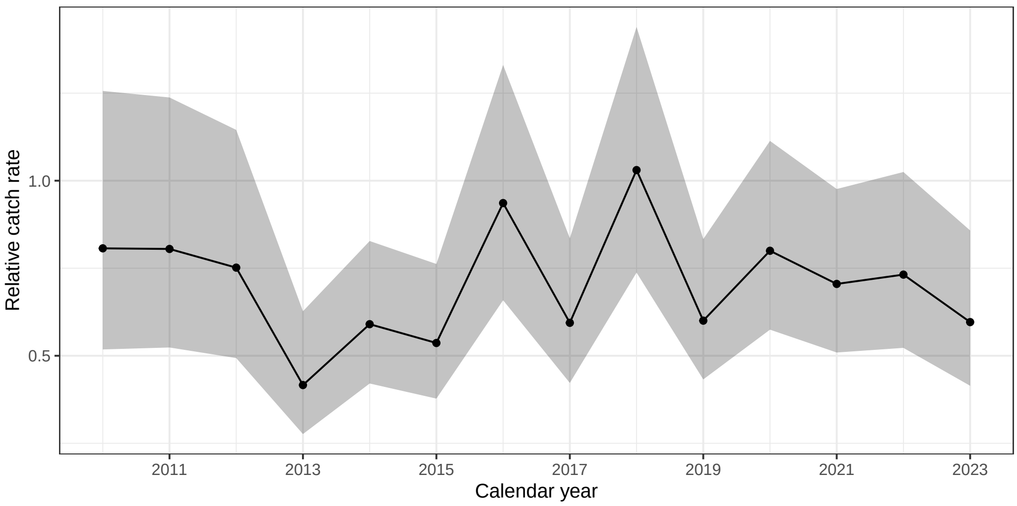

Figure 3.8: Annual standardised catch rates relative to average kg per hour (live weight) for herrmanni curryfish between 2010 and 2023 .

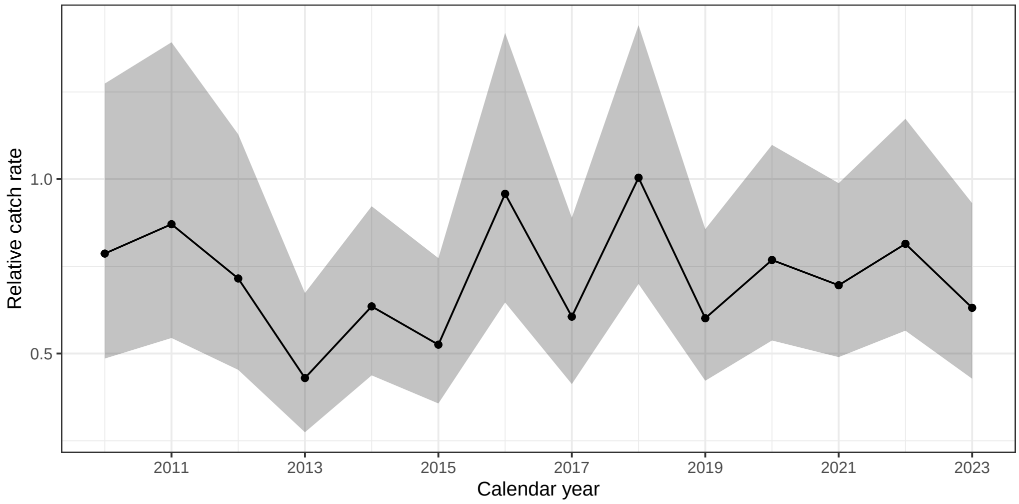

Figure 3.9: Annual standardised catch rates relative to average kg per hour (live weight) for vastus curryfish between 2010 and 2023 .

3.1.4 Length compositions

Length structures from the surveys are shown in (Figures 3.10, 3.11 and 3.12).

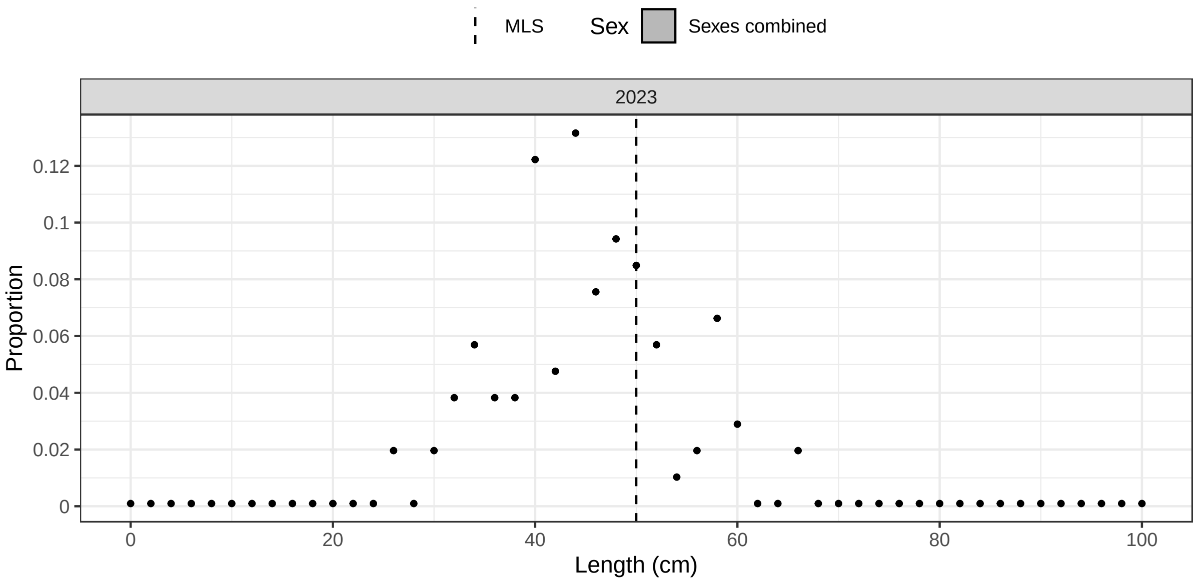

Figure 3.10: Length structures for the survey fleet for prickly redfish. The dashed vertical line indicates the MLS of 50 cm.

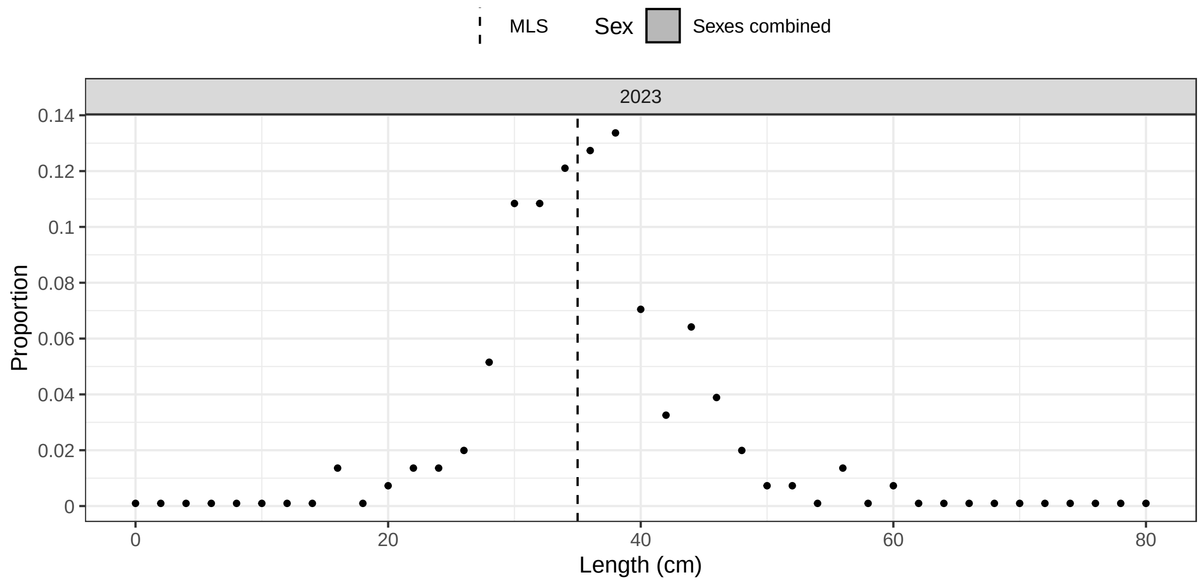

Figure 3.11: Length structures for the survey fleet for hermanni curryfish. The dashed vertical line indicates the MLS of 35 cm.

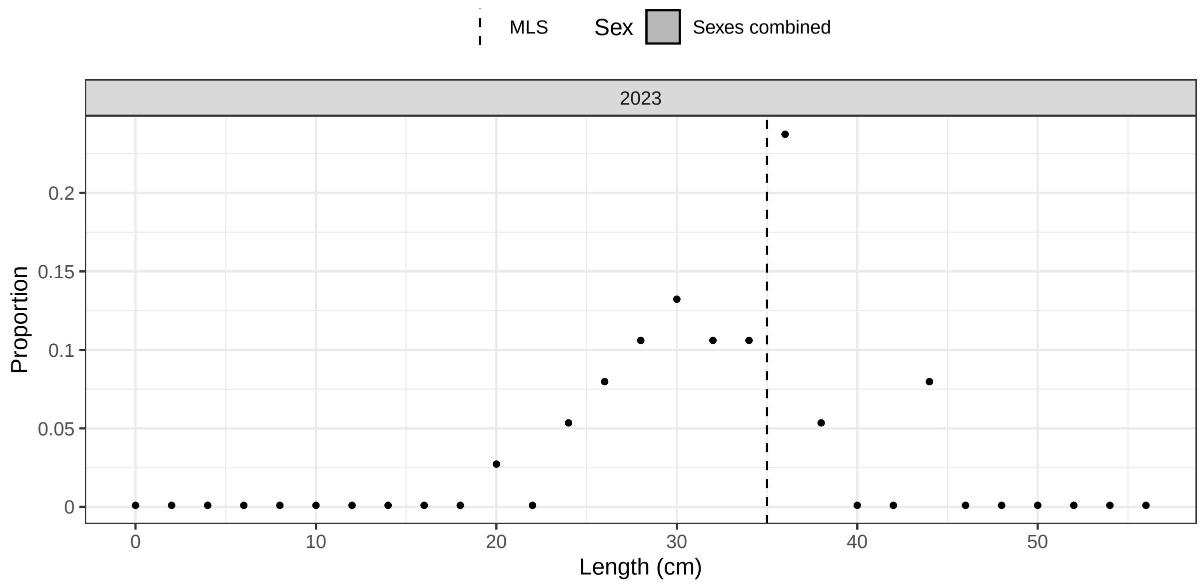

Figure 3.12: Length structures for the survey fleet for vastus curryfish. The dashed vertical line indicates the MLS of 35 cm.

3.2 Model outputs

3.2.1 Model parameters

A number of parameters were estimated within the models for each stock (Tables 3.1–3.3). The full list of estimated parameters is given for each SS and DDUST model scenario in Appendices F and G.

Table 3.1: Summary of parameter estimates from the base case Stock Synthesis and DDUST models for prickly redfish using MCMC. The estimates are the median of the paramater posteriors along with their standard deviations in parentheses.

Parameter	Stock Synthesis model estimate (Standard deviation)	DDUST model estimate (Standard deviation)
R_0◇	9.32 (0.29)	4.76 (0.12)
Survey selectivity inflection (cm)	43.15 (3.72)	
Survey selectivity width (cm)	11.8 (3.17)	
Catch rate variance (Q_extraSD in Stock Synthesis; σ_I in DDUST)	0.17 (0.05)	0.37 (0.06)

◇ R_0 is defined as the number of age-zero recruits in log space for Stock Synthesis and the number of legal-sized recruits in log space for DDUST.

Table 3.2: Summary of parameter estimates from the base case Stock Synthesis and DDUST models for herrmanni curryfish using MCMC. The estimates are the median of the paramater posteriors with their standard deviations in parentheses.

Parameter	Stock Synthesis model estimate (Standard deviation)	DDUST model estimate (Standard deviation)
R_0◇	9.42 (0.23)	6.37 (0.12)
Survey selectivity inflection (cm)	30.02 (3.77)	
Survey selectivity width (cm)	8.09 (6.76)	
Catch rate variance (Q_extraSD in Stock Synthesis; σ_I in DDUST)	0.09 (0.06)	0.21 (0.05)

◇ R_0 is defined as the number of age-zero recruits in log space for Stock Synthesis and the number of legal-sized recruits in log space for DDUST.

Table 3.3: Summary of parameter estimates from the base case Stock Synthesis and DDUST models for vastus curryfish using MCMC. The estimates are the median of the paramater posteriors along with their standard deviations in parentheses.

Parameter	Stock Synthesis model estimate (Standard deviation)	DDUST model estimate (Standard deviation)
R_0◇	9.79 (0.42)	4.97 (0.13)
Survey selectivity inflection (cm)	32.71 (1.98)	
Catch rate variance (Q_extraSD in Stock Synthesis; σ_I in DDUST)	0.08 (0.06)	0.21 (0.06)

◇ R_0 is defined as the number of age-zero recruits in log space for Stock Synthesis and the number of legal-sized recruits in log space for DDUST.

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

3.2.2 Model fits

Good fits were achieved for catch rate indices, survey biomass and length compositions (Appendix B).

3.2.3 Selectivity

Survey length selectivity was estimated within the Stock Synthesis model for the herrmanni curryfish and prickly redfish stocks and mirrored to commercial selectivity above the MLS (Figures 3.13; 3.14). For all three species, the MLS provided substantial protection from fishing as the MLS was large relative to species length at maturity and maximum size. For vastus curryfish, only the inflection point was estimated for selectivity with the width fixed through a two step process outlined in Section 2.5.4.

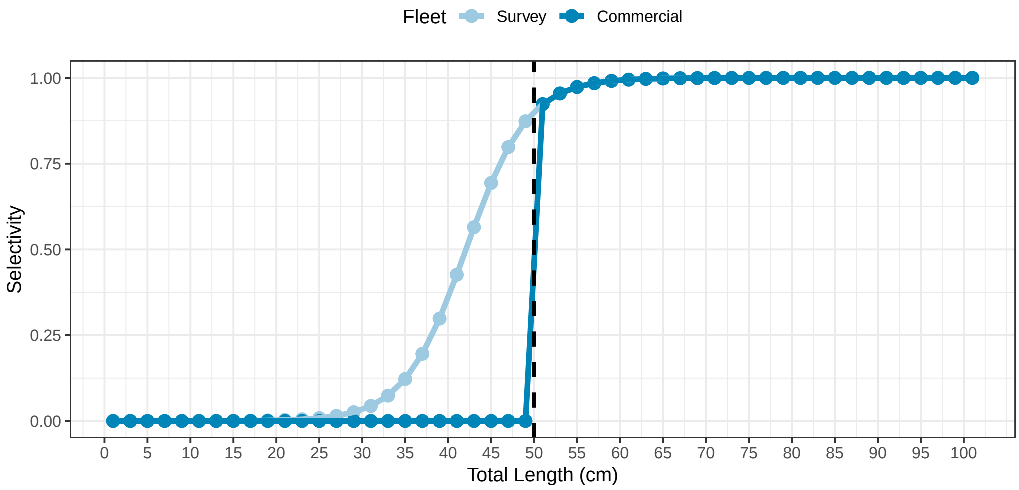

Figure 3.13: Estimated survey length selectivity and mirrored commercial selectivity for prickly redfish. The black dashed line represents the minimum legal size of 50 cm.

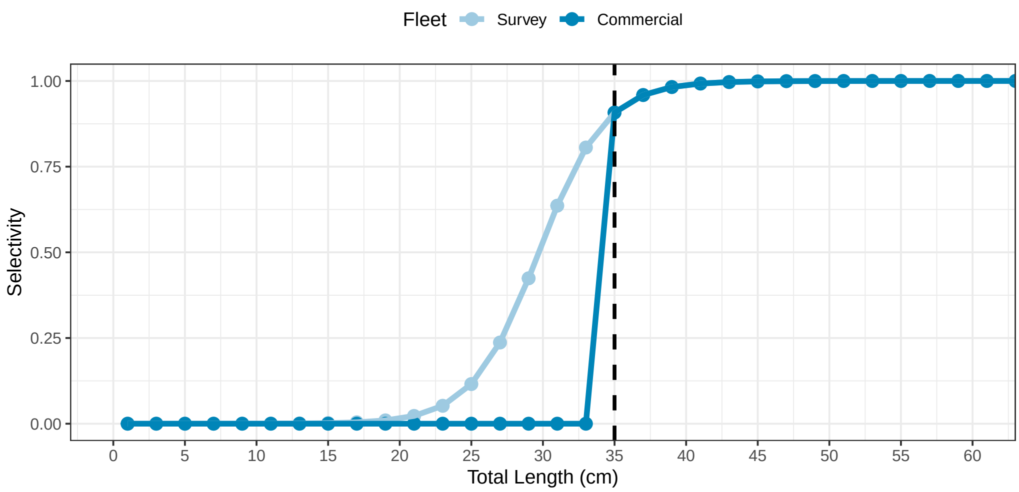

Figure 3.14: Estimated survey length selectivity and mirrored commercial selectivity for herrmanni curryfish. The black dashed line represents the minimum legal size of 35 cm.

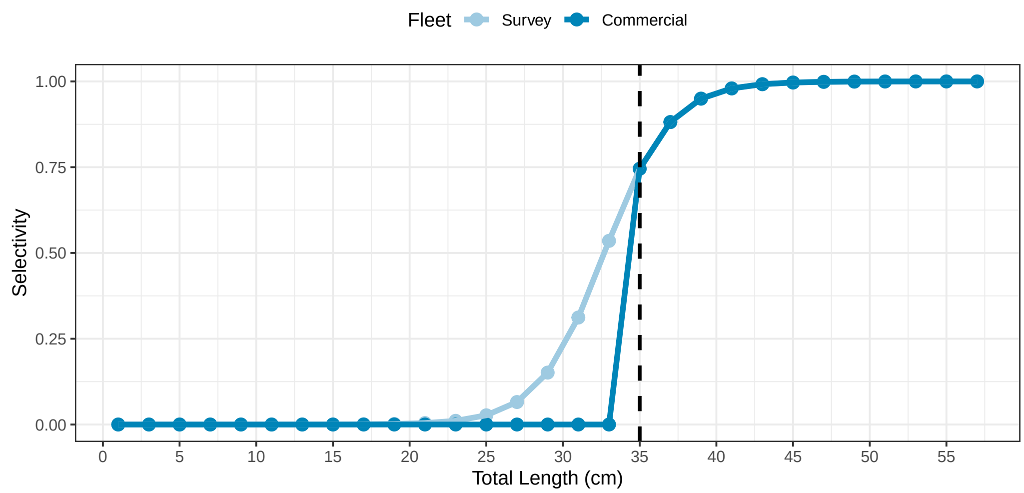

Figure 3.15: Estimated survey length selectivity and mirrored commercial selectivity for vastus curryfish. The black dashed line represents the minimum legal size of 35 cm.

3.2.4 Biomass

3.2.4.1 Prickly redfish

Fifteen model scenarios were run in Stock Synthesis for prickly redfish, covering a range of modelling assumptions and sensitivity tests. The base case Stock Synthesis results indicated that prickly redfish had a stable population, close to unfished levels of biomass for most of its exploitation history. The base case model indicated that the population increased to approximately 115% of unfished biomass in 2017 before decreasing to 91% of unfished biomass (73–116% range across the 95 percent credible interval) in 2023 (Figure 3.18). The absolute spawning biomass trajectory indicates the most likely virgin spawning stock size was 15679 t and the most likely current spawning stock size is 14350 t (Figure 3.19).

Relative biomass trajectories for all Stock Synthesis sensitivity scenarios except scenario 20 in which depletion in 1940 was 60%, are presented in Figure 3.19. In general, all scenarios – aside from Scenarios 2, 8 and 14 – followed a similar trend to the base case scenario. Scenario 2, in which the steepness was 0.5, estimated a higher relative biomass in 2023. Scenario 8, in which extra catch rate variance was estimated, resulted in a likely unrealistic biomass increase between 2016 and 2021. Scenario 14 in which the Ricker spawning recruitment relationship was applied, resulted in an unrealistically high biomass in 2023.

The Stock Synthesis base case scenario relative biomass trend is compared to the DDUST base case scenario in Figure 3.20. The DDUST model indicated a lower relative biomass estimate across the exploitation history. However, this relative biomass never declined below 60% in any year.

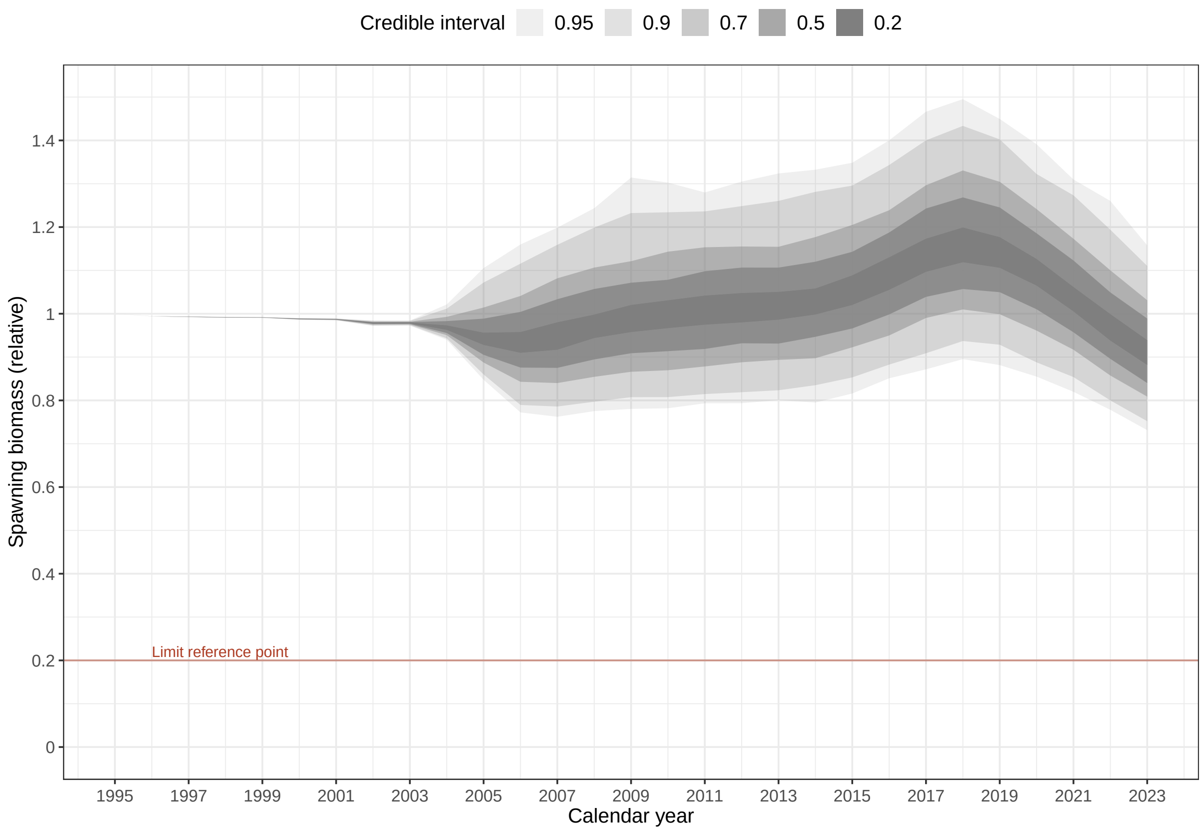

Figure 3.16: Estimated biomass trajectory relative to unfished from the base case Stock Synthesis model for prickly redfish, from 1995 to 2023.

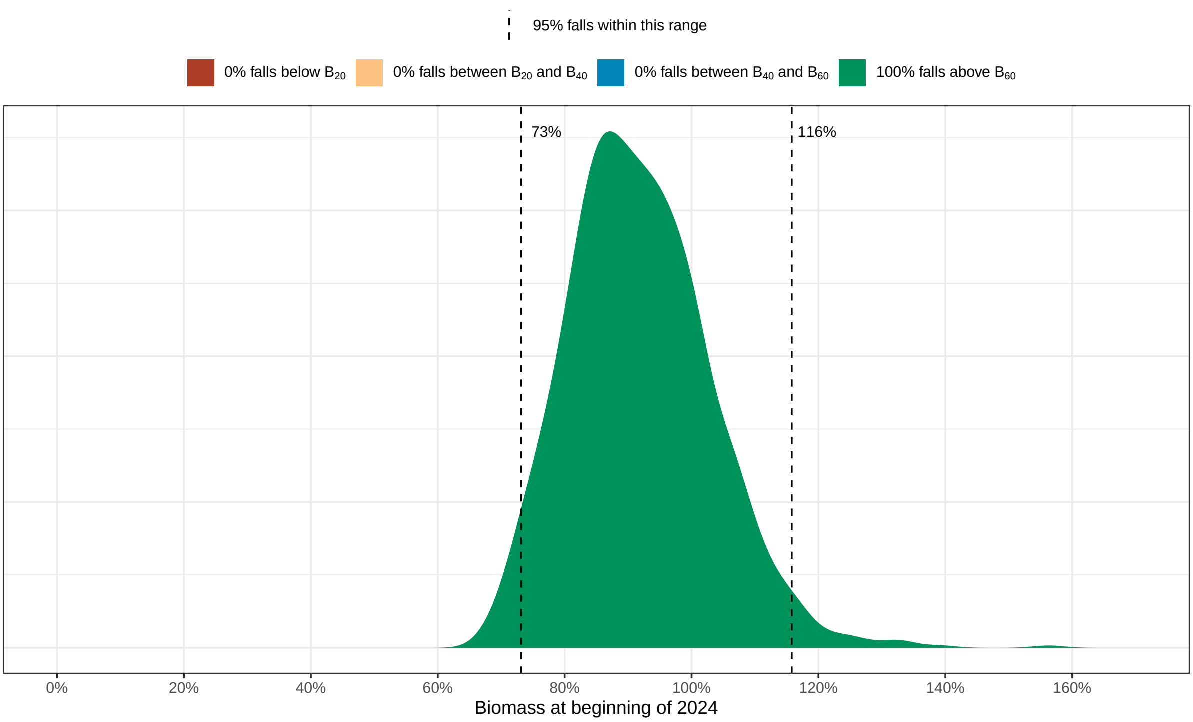

Figure 3.17: Probability distribution of the biomass ratio in 2023 for the base case Stock Synthesis model for prickly redfish with the credible interval and probability of biomass falling into the two categories indicated.

Table 3.4: Current and target indicators for Queensland east coast prickly redfish

Indicator	Value
Biomass ratio relative to unfished)	
Range (95% credible interval)	73–116%
Probability below 20%	0%
Probability between 20% and 40%	0%
Probability between 40% and 60%	0%
Probability above 60%	100%
Average five-year (2019 to 2023) retained commercial catch (boiled and frozen weight)	39 t

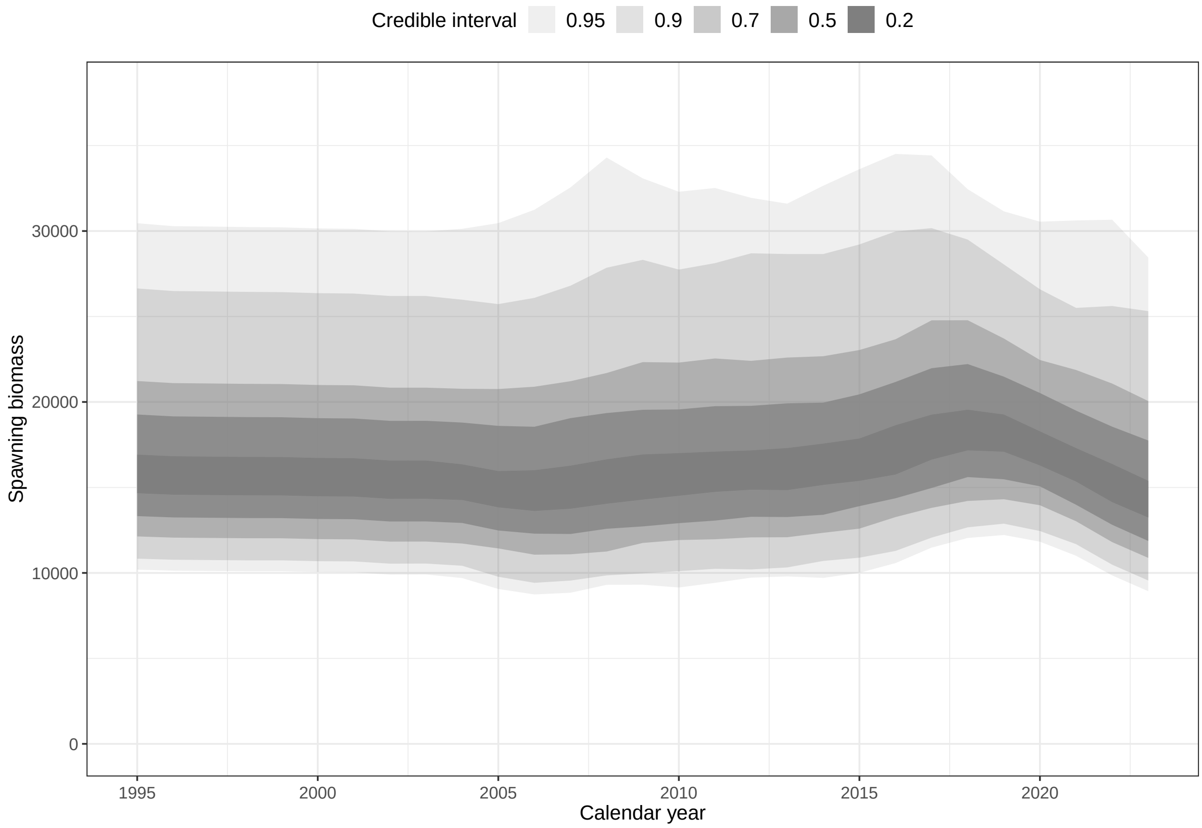

Figure 3.18: Estimated absolute spawning biomass trajectory from the base case Stock Synthesis model for prickly redfish, from 1995 to 2023.

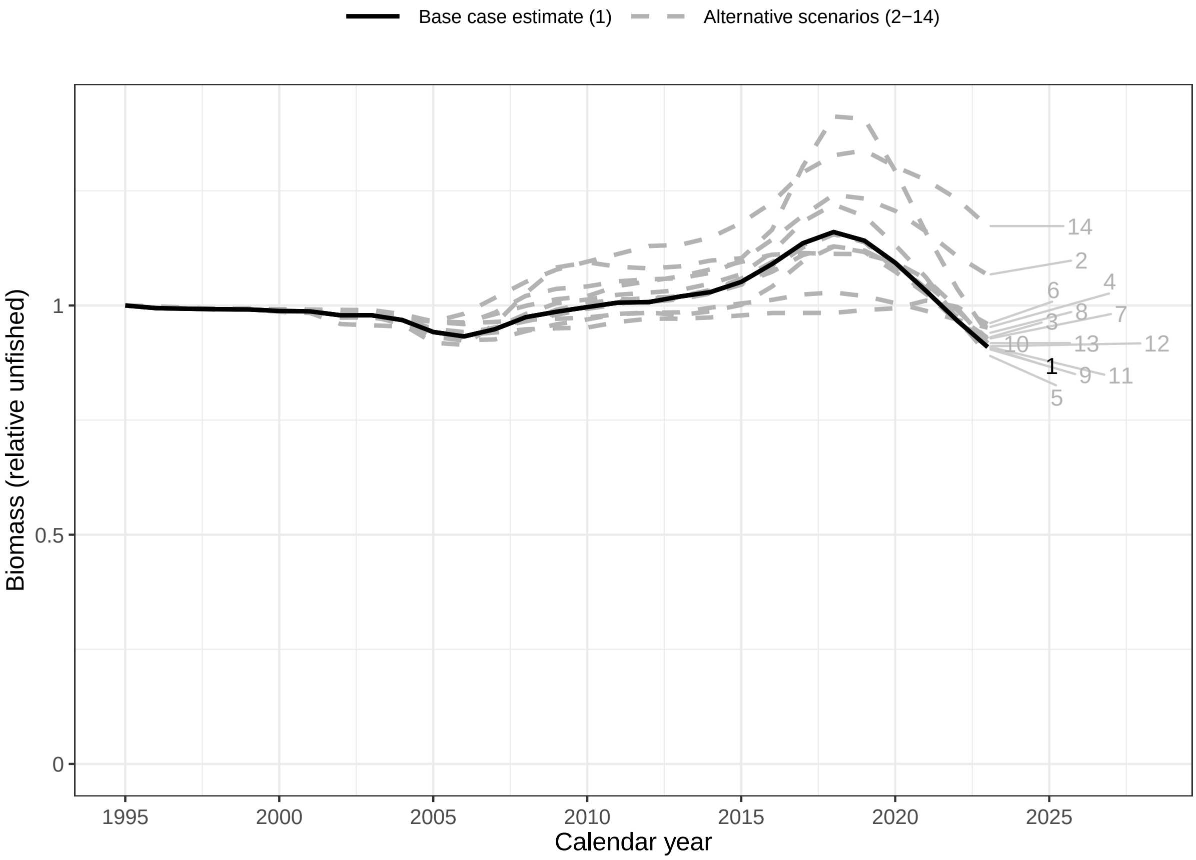

Figure 3.19: MCMC predicted biomass trajectory relative to unfished for prickly redfish, from 1995 to 2023 for fourteen (out of fifteen) Stock Synthesis model scenarios.

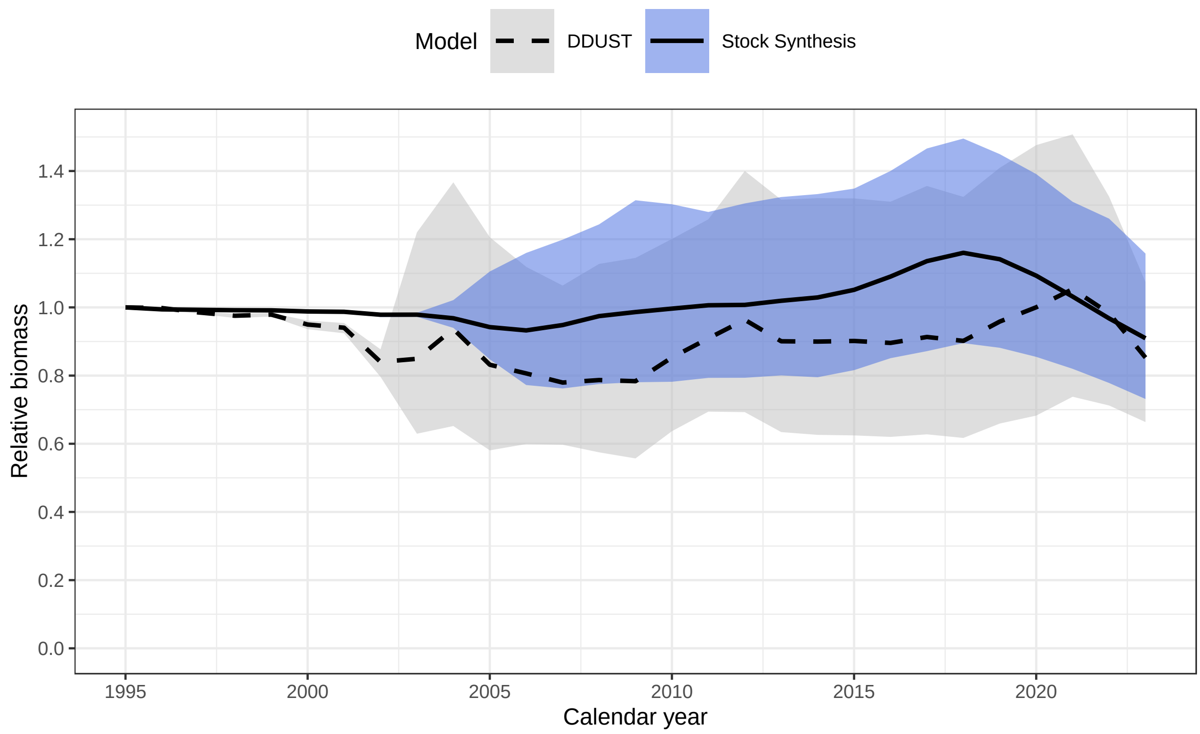

Figure 3.20: MCMC predicted biomass trajectory relative to unfished for prickly redfish, from 1995 to 2023 for the DDUST (grey shading and dashed black line) and Stock Synthesis (blue shading and solid black line) base case models. Note that the biomass presented for Stock Synthesis is spawning biomass while the biomass presented for DDUST is legal-size biomass.

3.2.4.2 Herrmanni curryfish

Seventeen model scenarios were run in Stock Synthesis for herrmanni curryfish, covering a range of modelling assumptions and sensitivity tests. The base case Stock Synthesis results indicated that herrmanni curryfish experienced a decline from the period 1995 to 2013 to reach 86% of unfished biomass. However, the population has increased since then and in 2023 the stock level was estimated to be 103% of unfished biomass (81–141% range across the 95 percent credible interval) (Figure 3.21).

The absolute spawning biomass trajectory indicates the most likely virgin spawning stock size was 14777 t and the most likely current spawning stock size is 15192 t (Figure 3.24).

Relative biomass trajectories for all Stock Synthesis sensitivity scenarios are presented in Figure 3.24. In general, all scenarios – aside from Scenarios 6, 7 and 15 – followed a similar trend to the base case scenario. Scenarios 6 and 7 included a lower value of *M* and Scenario 15 included the reported logbook catch instead of imputed catch. All estimated a likely unrealistic biomass increase beyond 2020. Scenario 14 included the Ricker spawner-recruitment relationship and estimated a slightly higher relative biomass.

The Stock Synthesis base case scenario relative biomass trend is compared to the DDUST base case scenario in Figure 3.25. Both models indicate similar depletion levels and the DDUST model results in larger uncertainty around the predicted trajectory.

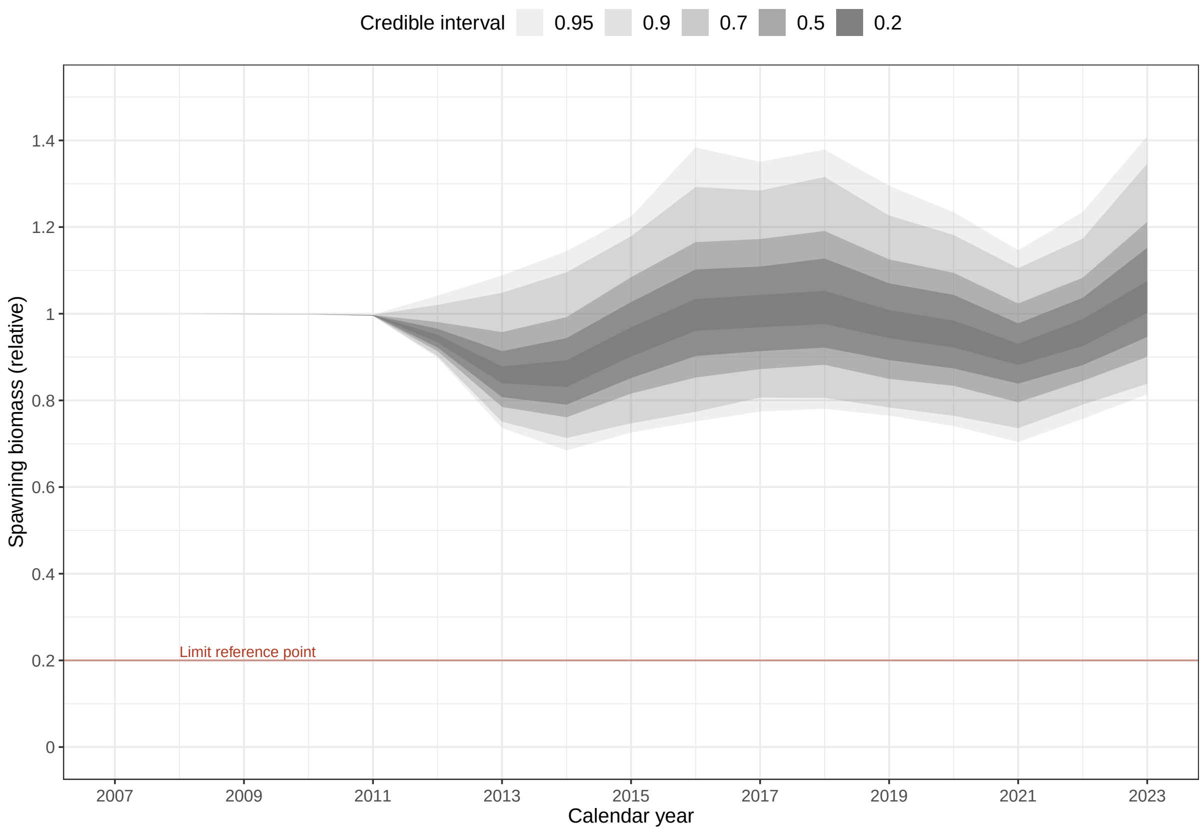

Figure 3.21: Estimated biomass trajectory relative to unfished from the base case Stock Synthesis model for herrmanni curryfish, from 2007 to 2023.

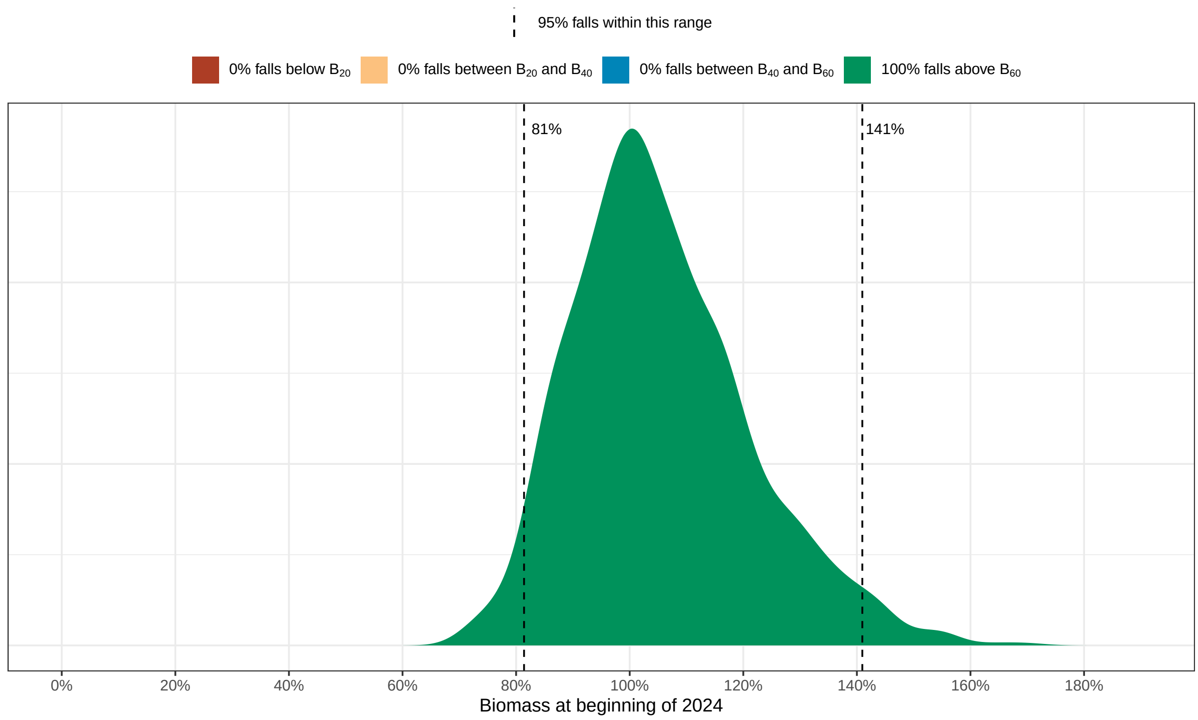

Figure 3.22: Probability distribution of the biomass ratio in 2023 for the base case Stock Synthesis model for hermanni curryfish with the credible interval and probability of biomass falling into the category indicated.

Table 3.5: Current and target indicators for Queensland east coast herrmanni curryfish

Indicator	Value
Biomass ratio relative to unfished)	
Range (95% credible interval)	81–141%
Probability below 20%	0%
Probability between 20% and 40%	0%
Probability between 40% and 60%	0%
Probability above 60%	100%
Average five-year (2019 to 2023) retained commercial catch (boiled and frozen weight)	36 t

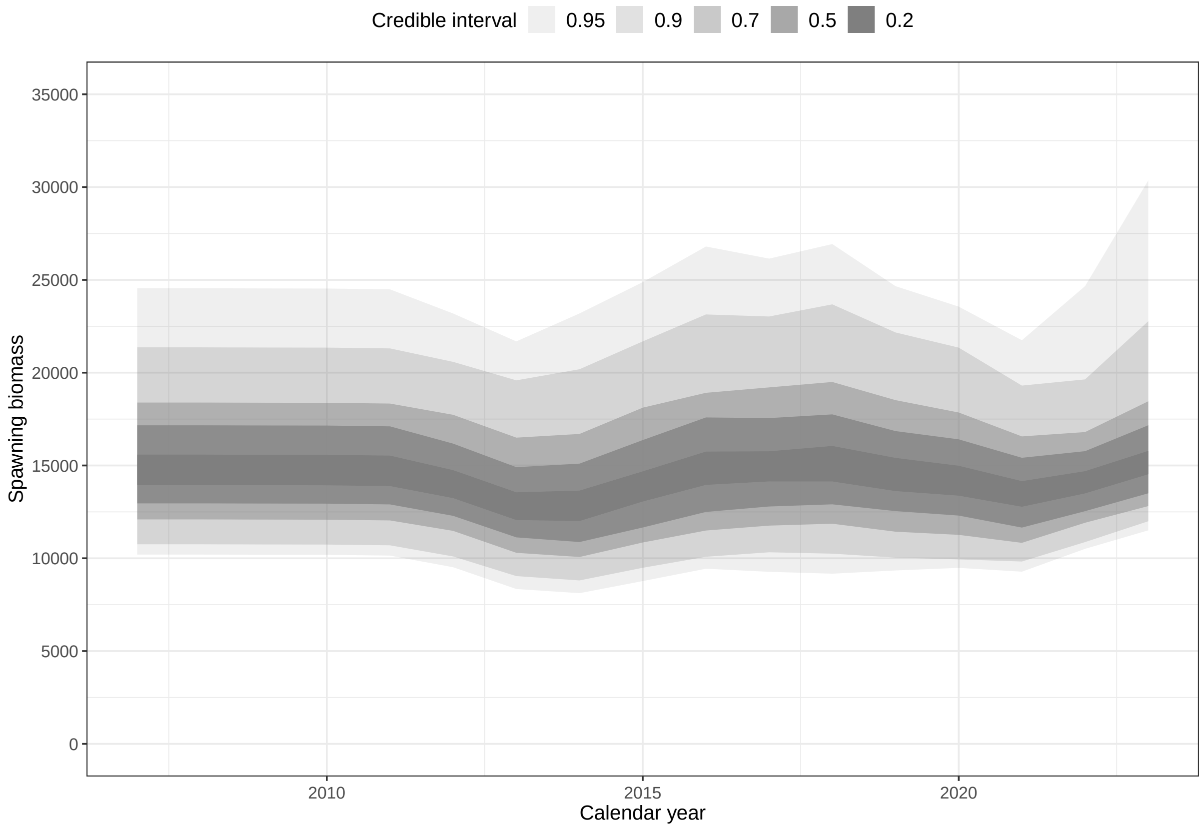

Figure 3.23: Estimated absolute spawning biomass trajectory from the base case Stock Synthesis model for herrmanni curryfish, from 2007 to 2023.

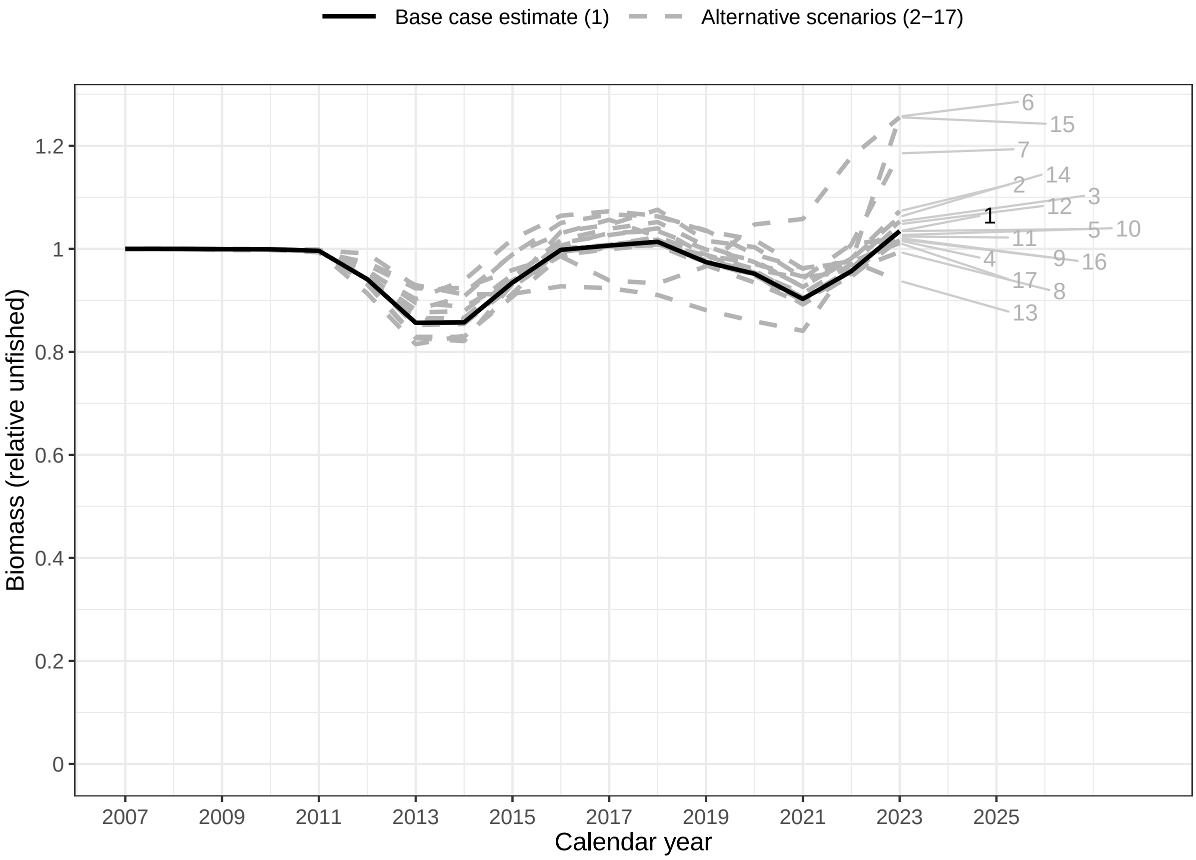

Figure 3.24: MCMC predicted biomass trajectory relative to unfished for herrmanni curryfish, from 2007 to 2023 for all Stock Synthesis model scenarios.

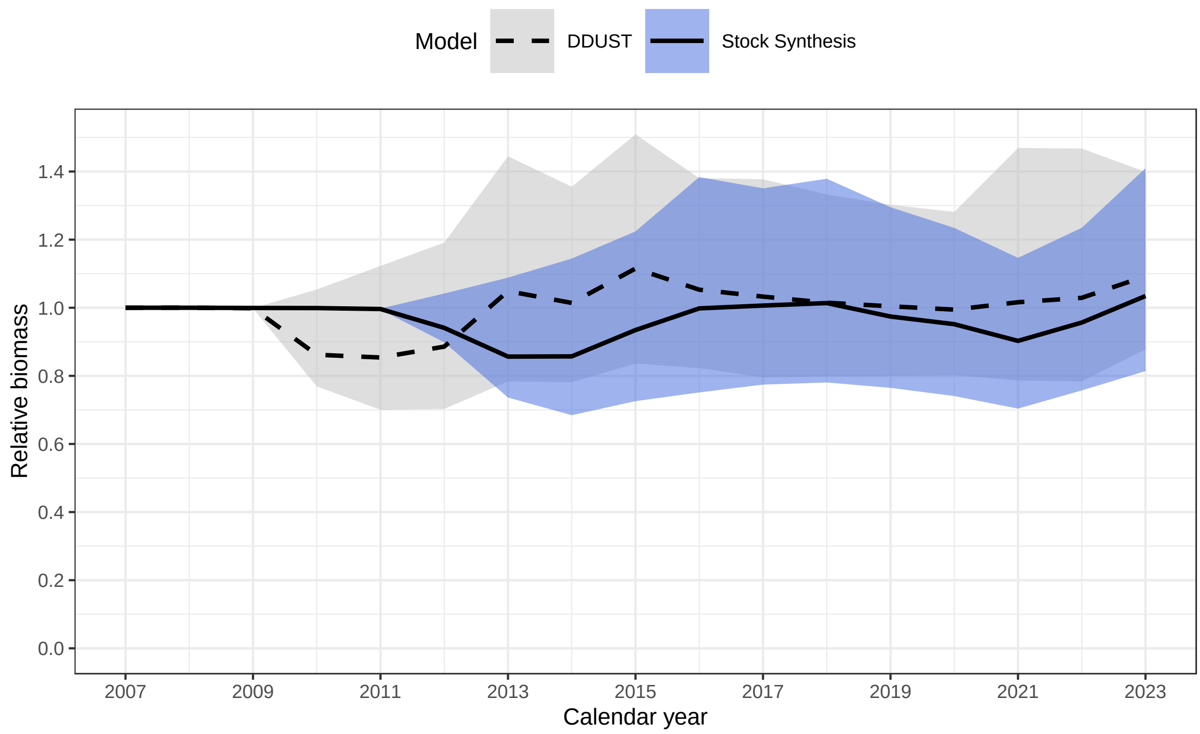

Figure 3.25: MCMC predicted biomass trajectory relative to unfished for herrmanni curryfish, from 2007 to 2023 for the DDUST (grey shading and dashed black line) and Stock Synthesis (blue shading and solid black line) base case models. Note that the biomass presented for Stock Synthesis is spawning biomass while the biomass presented for DDUST is legal-size biomass.

3.2.4.3 Vastus curryfish

Nineteen model scenarios were run in Stock Synthesis for vastus curryfish, covering a range of modelling assumptions and sensitivity tests. The base case Stock Synthesis results indicated that vastus curryfish remained close to unfished levels for most of its exploitation history with slight declines in recent years reducing its relative biomass to 87% of unfished biomass (65–124% range across the 95 percent credible interval) in 2023 (Figure 3.26).

The absolute spawning biomass trajectory indicates the most likely virgin spawning stock size was 4155 t and the most likely current spawning stock size is 3620 t (Figure 3.29).

Relative biomass trajectories for all Stock Synthesis sensitivity scenarios are presented in Figure 3.29. In general, all scenarios – aside from Scenarios 13 and 15 – followed a similar trend to the base case scenario. Scenario 13 included shrinkage adjustment for the length composition data and estimated a higher relative biomass, and Scenario 15 included the reported logbook catch instead of imputed catch and estimated a lower relative biomass, although this never declined below 60%. Scenario 14 included the Ricker spawner-recruitment relationship and estimated a higher relative biomass.

The Stock Synthesis base case scenario relative biomass trend is compared to the DDUST base case scenario in Figure 3.30. Both models indicate similar depletion levels and the DDUST model results in larger uncertainty around the predicted trajectory.

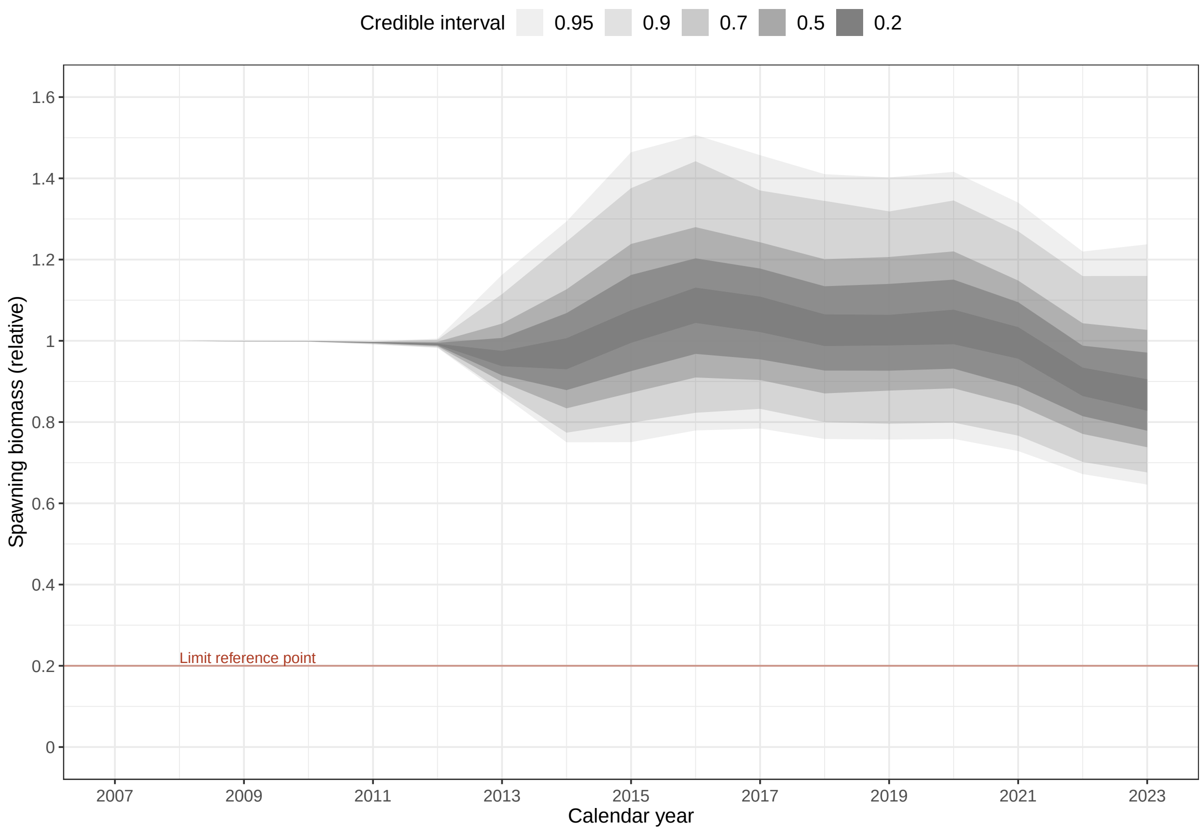

Figure 3.26: Estimated biomass trajectory relative to unfished from the base case Stock Synthesis model for vastus curryfish, from 2007 to 2023.

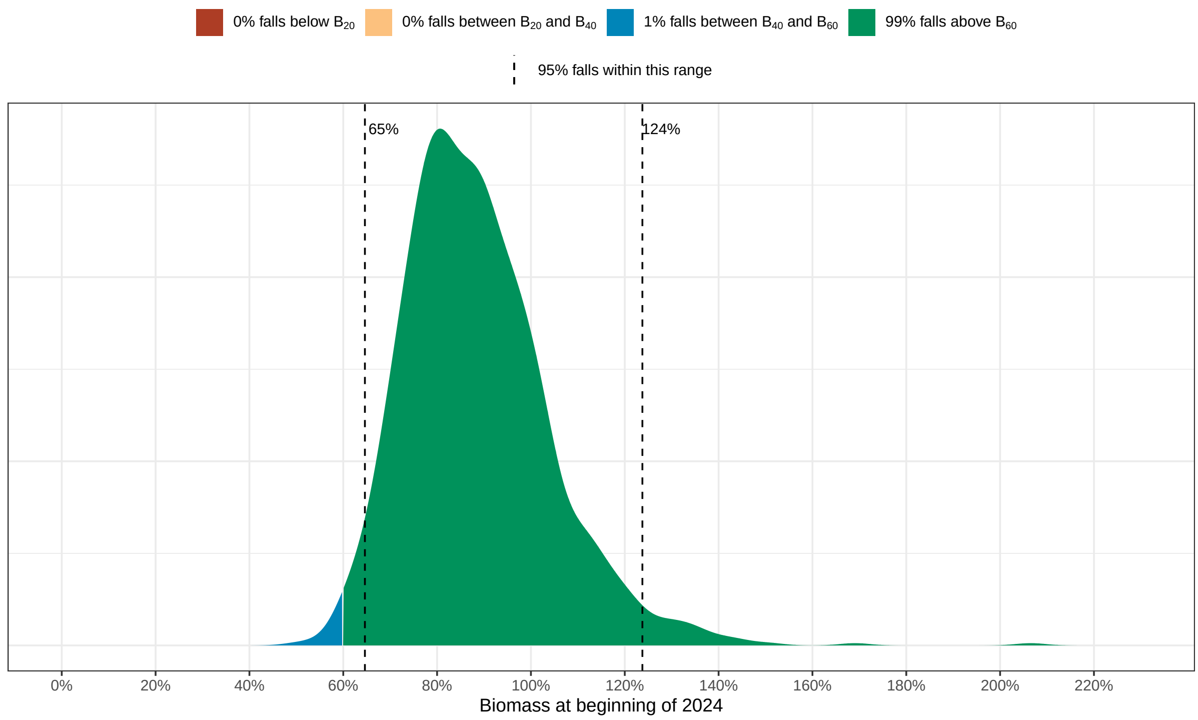

Figure 3.27: Probability distribution of the biomass ratio in 2023 for the base case Stock Synthesis model for vastus curryfish with the credible interval and probability of biomass falling into the two categories indicated.

Table 3.6: Current and target indicators for Queensland east coast vastus curryfish

Indicator	Value
Biomass ratio relative to unfished)	
Range (95% credible interval)	65–124%
Probability below 20%	0%
Probability between 20% and 40%	0%
Probability between 40% and 60%	1%
Probability above 60%	99%
Average five-year (2019 to 2023) retained commercial catch (boiled and frozen weight)	18 t

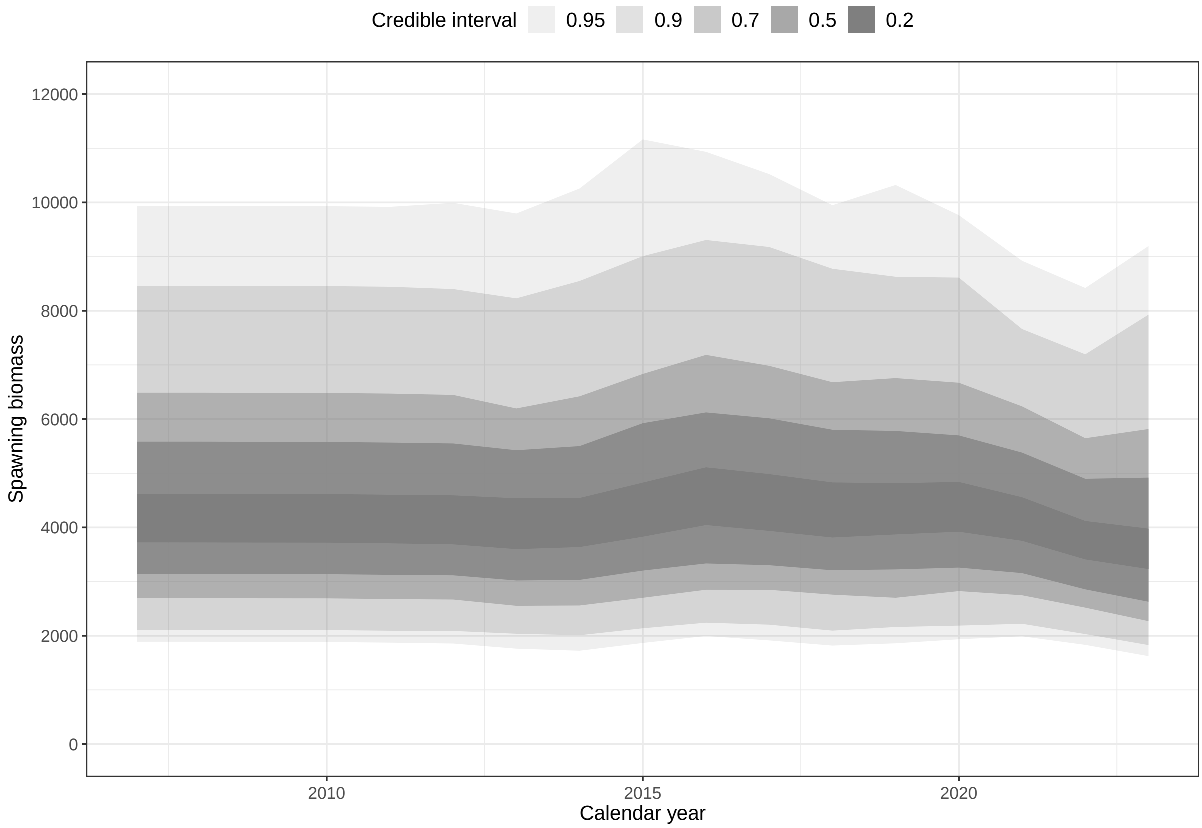

Figure 3.28: Estimated absolute spawning biomass trajectory from the base case Stock Synthesis model for vastus curryfish, from 2007 to 2023.

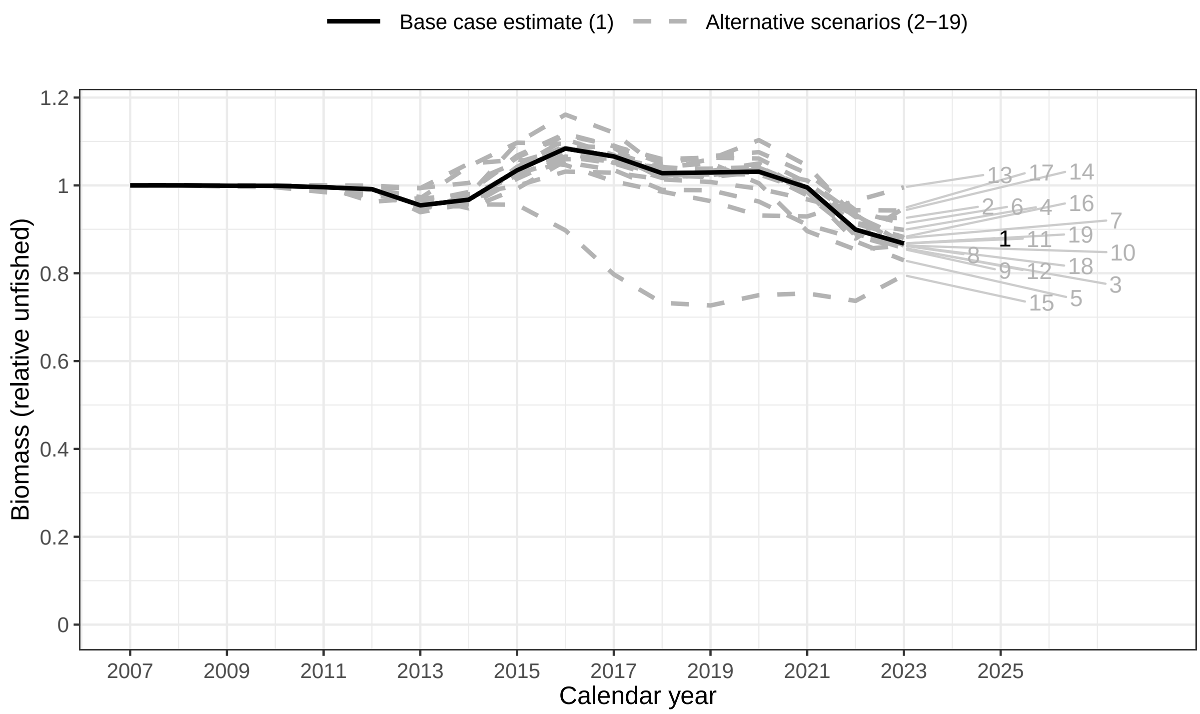

Figure 3.29: MCMC predicted biomass trajectory relative to unfished for vastus curryfish, from 2007 to 2023 for all Stock Synthesis model scenarios.

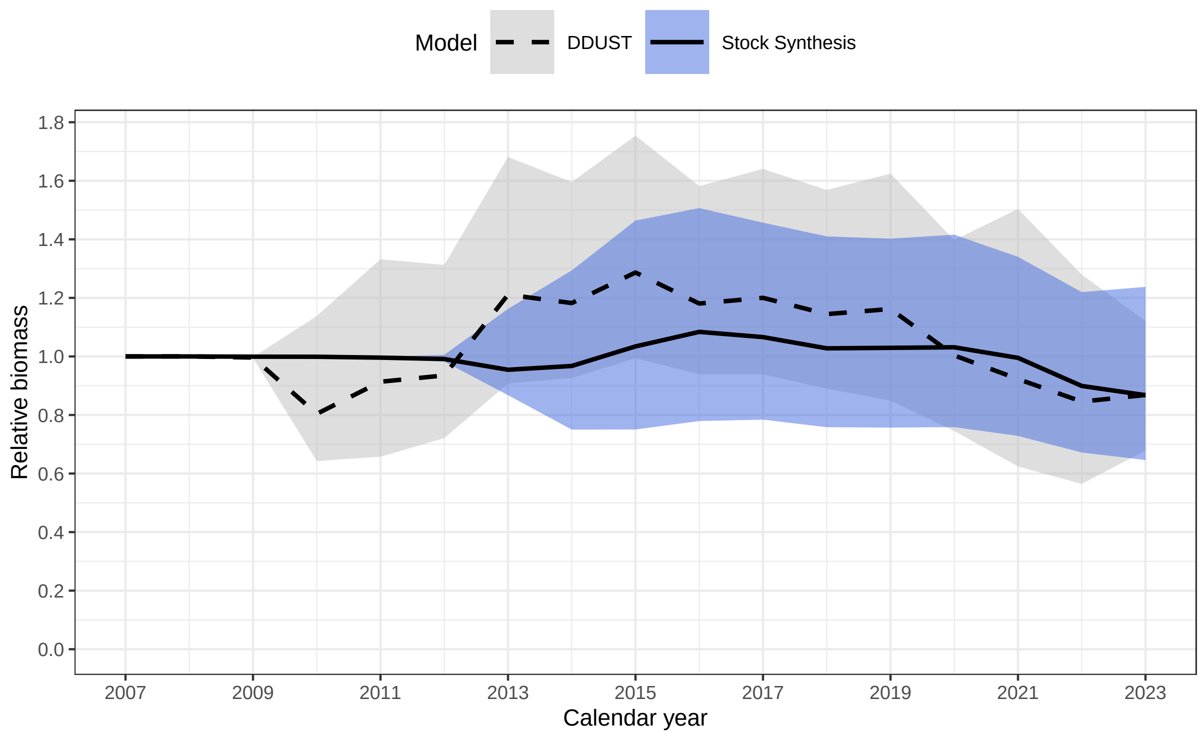

Figure 3.30: MCMC predicted biomass trajectory relative to unfished for vastus curryfish, from 2007 to 2023 for the DDUST (grey shading and dashed black line) and Stock Synthesis (blue shading and solid black line) base case models. Note that the biomass presented for Stock Synthesis is spawning biomass while the biomass presented for DDUST is legal-size biomass.

4 Discussion

4.1 Stock status

This was the first assessment of east coast prickly redfish, herrmanni curryfish and vastus curryfish by Fisheries Queensland. The base case models (Stock Synthesis and DDUST) demonstrated that all three species were above 60% of unfished biomass and have not been reduced below this level since the commencement of the fishery. Recent survey estimates of absolute biomass demonstrated large stock sizes relative to historical catch levels, indicating that these stocks have been lightly exploited since targeted fishing began. Additionally, the MLS of all three species are large relative to their maximum sizes, offering substantial protection to the majority of the populations. Accordingly, the stock assessments estimated low levels of F and high levels of relative biomass in 2023. Based on the Stock Synthesis model results the unfished levels of biomass were 91% for prickly redfish, 103% for herrmanni curryfish, and 87% for vastus curryfish. The DDUST model results were similar to those of Stock Synthesis for each stock.

There are a number of management measures in place which are providing substantial protection to each of these species. Large MLS have protected large components of the population, allowing sufficient opportunity for reproduction prior to harvest, rotational closures with effort limits have lowered the probability for localised depletion to occur and catch triggers have been implemented to avoid overfishing. While these catch triggers were determined from recent average catches, these appear appropriate. Prickly redfish has now been harvested for almost thirty years, with stable levels of catch and catch rates, while recent surveys demonstrate a high level of biomass. This evidence suggests that exploitation has been light and most of the stock has been protected through a large MLS. This is reflected in the assessment models that used this information. A much shorter time series exists for herrmanni curryfish and vastus curryfish, although evidence suggests that these stocks are similarly healthy and have also been well managed.

4.2 Performance of the population model

Two different stock assessment models were applied to account for the data limited nature of these assessments. Routine collection of lengths, ages and weights has not been undertaken for the fishery and the only data available for all three species were catch, catch rates, and a single estimate biomass and length composition from recent surveys (Koopman et al. 2024). The Stock Synthesis model makes full use of all these data sources, allowing selectivity and the MLS to be accounted for in the stock assessment process. However, Stock Synthesis requires biological information on growth and maturity that are unknown for vastus curryfish while only maturity was known for herrmanni curryfish. Alternatively, DDUST (a delay-difference model) does not require this biological information but does not consider population structure, nor selectivity and MLS. Rather than selecting one of these models *a priori* and accepting these compromises, both models were applied to these species and their results compared. Both models performed adequately across most scenarios for the three species, and Stock Synthesis selected as the primary model for this assessment. This choice was made as Stock Synthesis consistently provided the best fit to surveyed biomass and considers an MLS (a key management measure for the fishery), thus providing more valuable outputs than DDUST. Despite Stock Synthesis requiring assumed parameters for growth and maturity, the DDUST model did not provide contrary conclusions. Sensitivity analyses focusing on growth and maturity also did not measurably change the Stock Synthesis results. Therefore, while assuming biological parameters was not ideal and their acquisition should be a principal focus of future research, Stock Synthesis was able to adequately model these species.

It should be noted that these assessments are data-limited and therefore these results should be treated with appropriate conservatism. The agreement between multiple stock assessment models across most scenarios demonstrates that their conclusions on stock status are well supported by the data. However, as more data becomes available, these models and their performances are will be refined which can lead to updated results based on new information. With the potential for species biology to be better resolved, further considerations of catch rate analyses and the possibility of additional surveys, future model outputs may differ once these new data are included. This is a standard risk that applies to all data-limited stock assessment situations. Therefore, the outcomes of this assessment should be treated as the best available information, noting that it will be continually improved over subsequent assessments.

4.2.1 Stock Synthesis

The Stock Synthesis base case models performed best for all three species in terms of model fit and plausibility of results (relative and absolute biomass, recruitment deviations and *F*). All models converged cleanly when estimated with MLE and MCMC model diagnostics showed results had acceptable levels of uncertainty in parameter estimation. The MCMC estimated results did not differ considerably from the MLE results and are presented as the main results throughout this assessment.

Fifteen, seventeen and nineteen scenarios were applied for the prickly redfish, herrmanni curryfish and vastus curryfish, respectively. For all species, the use of the Ricker spawner-recruitment relationship resulted in a higher relative biomass. For prickly redfish, most scenarios provided results that were not consequentially different from the base case models. The scenarios with extra catch rate variance and initial depletions resulted in a higher relative biomass. For herrmanni curryfish and vastus curryfish, most scenarios provided results that were not consequentially different from the base case models. The scenario that used logbook reporting for herrmanni curryfish and vastus curryfish (Scenario 15) was different to the base case, providing a relative biomass estimate in 2023 that was higher for herrmanni curryfish, but lower for vastus curryfish. This scenario indicates the importance of catch history on model outcomes. Future work that provides information on historical catches would be justified. Scenario 6, which used a lower value of *M*, provided different and contrasting results between species. This scenario for herrmanni curryfish caused a higher and unrealistic 2023 relative biomass estimate. Meanwhile this scenario caused flatter biomass trajectory for prickly redfish.

4.2.2 DDUST

The DDUST base case models performed best for all three species in terms of model fit and plausibility of results (relative and absolute biomass, recruitment deviations and *F*). All models converged cleanly when estimated with MLE and MCMC model diagnostics showed results with acceptable levels of uncertainty in parameter estimation. Despite being an inherently different model to Stock Synthesis, DDUST provided similar results across stocks and scenarios. However, DDUST did not fit well to legal-sized biomass estimates in most scenarios for all three species.

4.2.3 Natural Mortality (*M*) pre-specification

Scenario 6, which used a lower value of *M*, provided different results to the base case for prickly redfish and hermanni curryfish. Evidence suggests that sea cucumbers are slow growing, and can achieve reasonably old ages (Purcell et al. 2016; Uthicke et al. 2004), suggesting that M may be quite low for many species. However, there is limited information on life history to inform estimates of M for many species. While an estimate of M was available for prickly redfish and based off of life history information (Conand 1993), the pre-specified values of M were sourced from the MSE conducted by Skewes et al. (2014) for both curryfish species. Given the uncertainty in M, and its importance in stock assessments, these base case values were sensitivity tested through additional scenarios. A lower value of $M = 0.3\ \text{yr}^{-1}$ yielded a different biomass trajectory for two of the three species but had little support in comparison to the base case models. Likelihood profiles of M were not significantly different for any of the DDUST models (i.e., the log-likelihood differences were less than two), nor the Stock Synthesis models for prickly redfish and vastus curryfish. Meanwhile, the Stock Synthesis likelihood profile for herrmanni curryfish showed greater support for higher levels of M, rather than lower ones. Therefore, while a lower values of M may be considered given sea cucumber biology, there was no support from any of the data considered in this assessment for a lower value to be pre-specified.

4.3 Unmodelled influences

4.3.1 Stock structure assumptions

Previous research has recommended that Queensland sea cucumber populations be considered as sub-populations that contribute to a larger meta-population (Wolfe et al. 2022). While ideal, this is not possible with the current data and information available for species caught in the QSCF. From the information available, it is likely that prickly redfish populations are reasonably well mixed despite relatively local larval transport and significant levels of self seeding (Skewes 2023). Consequently, consideration of prickly redfish in this assessment as a single stock is deemed appropriate but local population dynamics should also be considered (Skewes 2023).

Considering species that could have reef level meta-population dynamics as a single well mixed stock in stock assessment models could risk localised depletion going undetected. However, this risk was reduced for these species by the RHA which is a key management measure implemented in the QSCF. Its main goal is to maintain high sea cucumber densities across the GBR and minimise the possibility of localised depletion. Therefore, the risk associated with considering a broad stock structure for these species is reduced by their spatial fisheries management. Despite this, it will remain important to gain an improved understanding of recruitment dynamics and stock structure for these species, and others, in the QSCF.

4.3.2 Marine park zoning

Prickly redfish has had a longer exploitation history than most Queensland sea cucumber species with catches commencing in 1995, prior to the GBRMP rezoning. Conversely, herrmanni curryfish and vastus curryfish catches did not occur until after the GBRMP was re-zoned. Therefore, prickly redfish have historically been harvested from areas that were previously closed to fishing, while herrmanni curryfish and vastus curryfish populations in green and yellow zones are unfished. As a result, 37% of the GBRMP has never been fished for these two species and little to no information is available from these areas to be included in stock assessments. While catch records for prickly redfish do predate the GBRMP re-zoning, location information was not collected in logbooks during this period. Therefore, there is no logbook information on any of theses species that can be used to model populations in closed areas. Some limited sampling occurred in green zones in the recent biomass survey (Koopman et al. 2024), but this alone is insufficient to model these areas. This assessment has therefore only modelled the portion of populations open to fishing. This offers a further level of conservatism to this assessment given the potential protection of the green and yellow zones. However, a better understanding of these populations and how they influence species recruitment would benefit this assessment.

4.3.3 Environmental/climatic influences

Environmental variables such as heat, wind, cyclones, rainfall, and tides could be drivers of sea cucumber abundance; none of which were included as variables in the catch rate standardisation or in the stock assessment model as environmental parameters. These variables will have an influence on natural mortality and recruitment success and could explain variability in abundance indices if appropriately included in analyses. Furthermore, climate change impacts on GBR are expected to increasingly affect marine populations (Rogers et al. 2017; Welch et al. 2014) and it is unlikely that sea cucumbers will be immune to these impacts.

4.3.4 Multi-species fishery dynamics

The QSCF is a multi-species fishery that collects up to twenty-two species (Fisheries Queensland 2021) which can pose complications if targeting is not accurately accounted for in catch rate standardisation (Hoyle et al. 2024). Multi-species fisheries can also have their dynamics driven by market forces such as changing species values. This can impact catches if market opportunities cause fishers to target other species. Therefore, trends in catches can be more related to fishery economic decision making than stock status. This increases the importance of stock assessments in fisheries such as the QSCF as unexplained catch declines have been interpreted as issues with stock status and serial species depletion (Eriksson et al. 2015; Wolfe et al. 2022).

4.4 Recommendations

4.4.1 Data

Life history and biological information is often missing or incomplete for sea cucumber species (Friedman et al. 2011; Purcell et al. 2013). In this assessment, available biological information was relatively complete for prickly redfish, partly complete for herrmanni curryfish and mostly lacking for vastus curryfish. The incompleteness of life history information was overcome in this assessment by applying two stock assessment models and testing the sensitivity of these to assumed biological parameters. However, this is not a long-term substitute for missing biological data and these information gaps need to be filled.

Fine scale spatial information of fishing activities can be particularly valuable in dive fisheries where catch rates can be highly hyperstable. Fisher hour expresses effort as a unit of time only, while space use can be a more appropriate or complementary unit of effort (Mundy 2012). As dive area increases to account for reduced densities then catch rates decline, providing more information to stock assessments. Dive logger and GPS technology has been trialled in abalone fisheries and is now in operation in several Australian jurisdictions (Mundy 2012). They can also only provide indices of abundance once they have been in use long enough to create a sufficient time series. The Fisheries Queensland vessel monitoring system (VMS) is in operation in the QSCF, although it is not in use on the tender vessels and thus cannot be used to measure fishing effort on a spatial scale. Despite this, advances in data collection would undoubtedly provide valuable effort information for future assessments. However, while these additional data sources are valuable, they require investment of both time and money.

4.4.2 Monitoring

The biomass estimates and length compositions were vital inputs to this assessment. These biomass estimates essentially anchor the stock assessment model to an accurate absolute biomass level with the relative biomass trajectory estimated from the remaining model inputs. This indicates the importance of this information, not only for these assessments, but also for any other sea cucumber species in the QSCF that may be assessed in the future.

While a single estimate of biomass is clearly valuable to these stock assessment models, multiple estimates that create a time series will add further value. Currently, selectivity is estimated from a single year of length frequency data and there will be some bias introduced depending on how much recent recruitment has influenced population length structure at the time of the survey. Additional years of length compositions attained from biomass surveys will reduce this bias. Furthermore, a time series of biomass estimates will provide empirical estimates of population productivity when combined with retained catch over the same period. This will occur as the biomass trajectory between surveys can be better quantified and the model can consider the relative contribution of catch (removals) and recruitment (additions) to the population that would cause this trend. Stock assessments that have been built using long time series of absolute abundance from surveys have benefited greatly from this and have been able to estimate productivity parameters (such as M) which are rarely attempted in other assessments (Grammer et al. 2021). Therefore, while substantial benefits to this assessment have been realised through the availability of a single survey estimate, there remains opportunity for additional surveys to provide additional benefits.

4.4.3 Management

The QSCF harvest strategy (Fisheries Queensland 2021) states that all sea cucumber species must be maintained at, or returned to, a target exploitable biomass level that achieves maximum economic yield, defined as 60% virgin biomass. All three species are above this level in 2023 and have not declined below 60% during their exploitation history.

4.4.4 Assessment

Future assessments could be improved by:

- **Further consideration of catch rates.** Currently, catch rate standardisation contains a few key factors such as vessel and month. This occurs as the small fleet size produces collinearity among many variables based on the fishing operations of only a few vessels. For example, fishing records in a particular grid and month often occur from only a single vessel and therefore their individual effect sizes cannot be estimated. Further extending catch rate standardisation to consider additional variables of interest, such as environmental variables, would benefit these assessments given their data limited nature. In addition, changes in catchability through time have not been applied in this assessment. Such changes can be difficult to quantify and the data limited nature of this assessment provides additional impediments to this. Nonetheless, future assessments would benefit from the consideration and testing of time-varying catchability.
- **Considering stock recruitment depensation.** The slow recovery rate of sea cucumbers following overfishing has led to suggestions of recruitment depensation occurring through the Allee effect (Friedman et al. 2011; Bell et al. 2008). While this is certainly possible, depensation is exceptionally difficult to model and assess in stock assessments (Liermann et al. 1997). This is because recruitment needs to be accurately modelled across a range of relative biomass levels so that the

shape of the resulting depensatory effects can be modelled at lower population sizes (Liermann et al. 1997). This is difficult to achieve for data rich assessments where periods of high and low stock sizes have occurred, let alone for data limited stocks, such as these three species, where evidence suggests that overfishing has not occurred. While this is likely not an area that can be addressed in these assessments, ability to understand and account for potential depensatory effects would be generally valuable in future sea cucumber assessments.

- **Consider age dependent natural mortality** This assessment considers estimates of *M* that are time, length, and age dependent. Sensitivity testing of these values demonstrated little impact on the conclusions of the assessment. However, the consideration of a length or age dependent *M* would provide more biological realism. There is evidence of low *M* occurring for large sea cucumbers while less information is available on smaller individuals that are more cryptic prior to recruitment to the fishery. It is possible that *M* could be high for individuals at smaller sizes (hence their cryptic nature) and that mortality is reduced with age and size. As a result, consideration of size dependent *M* using techniques such as Lorenzen (1996) could be warranted. However, this would require greater information on length-at-age before it could be appropriately implemented for all three species assessed here.

4.5 Conclusions

This assessment was commissioned to establish the status of Queensland's east coast prickly redfish, herrmanni curryfish and vastus curryfish populations. The converged scenarios suggested current biomass (compared to unfished levels) for prickly redfish stock is 91% (73–116%), for herrmanni curryfish stock is 103% (81–141%), and for vastus curryfish is 87% (65–124%). Some recommendations for future work have been made.

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Appendix A Model inputs

A.1 Abundance indices

A.1.1 Catch rate standardisation diagnostics

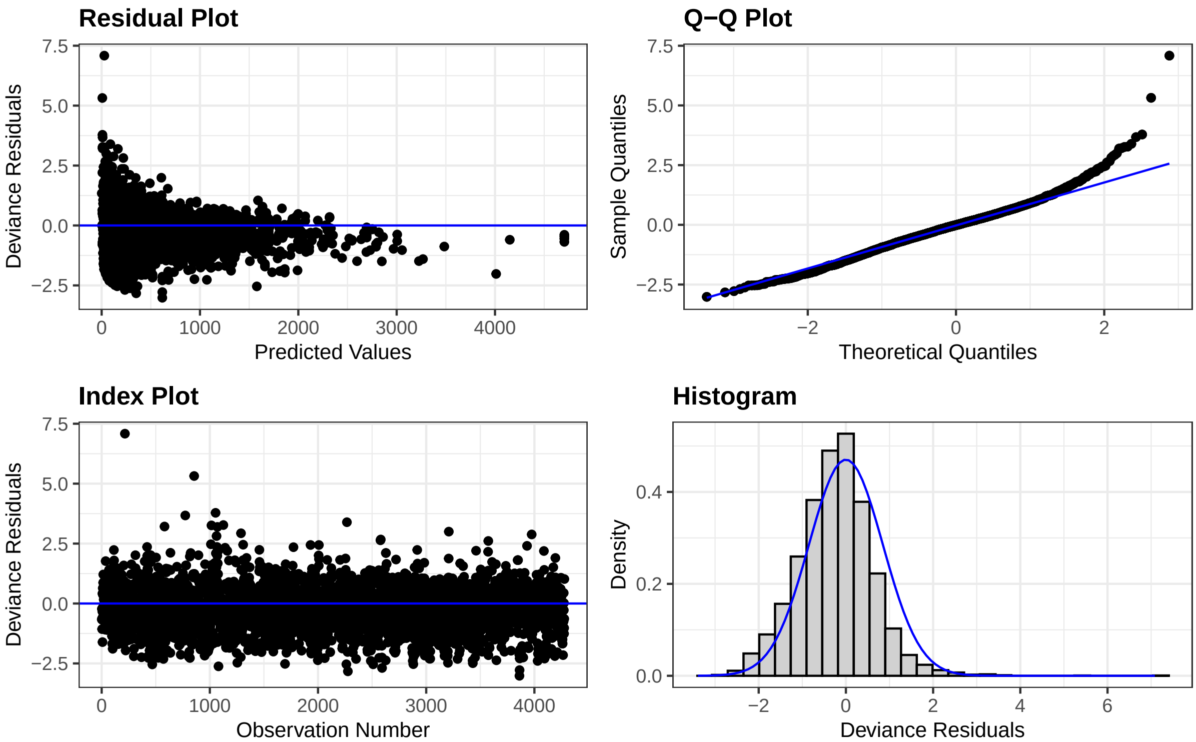


Figure A.1: Catch rate diagnostics for prickly redfish. There were no influential standardised-residuals, beyond the values of -2 and 2.

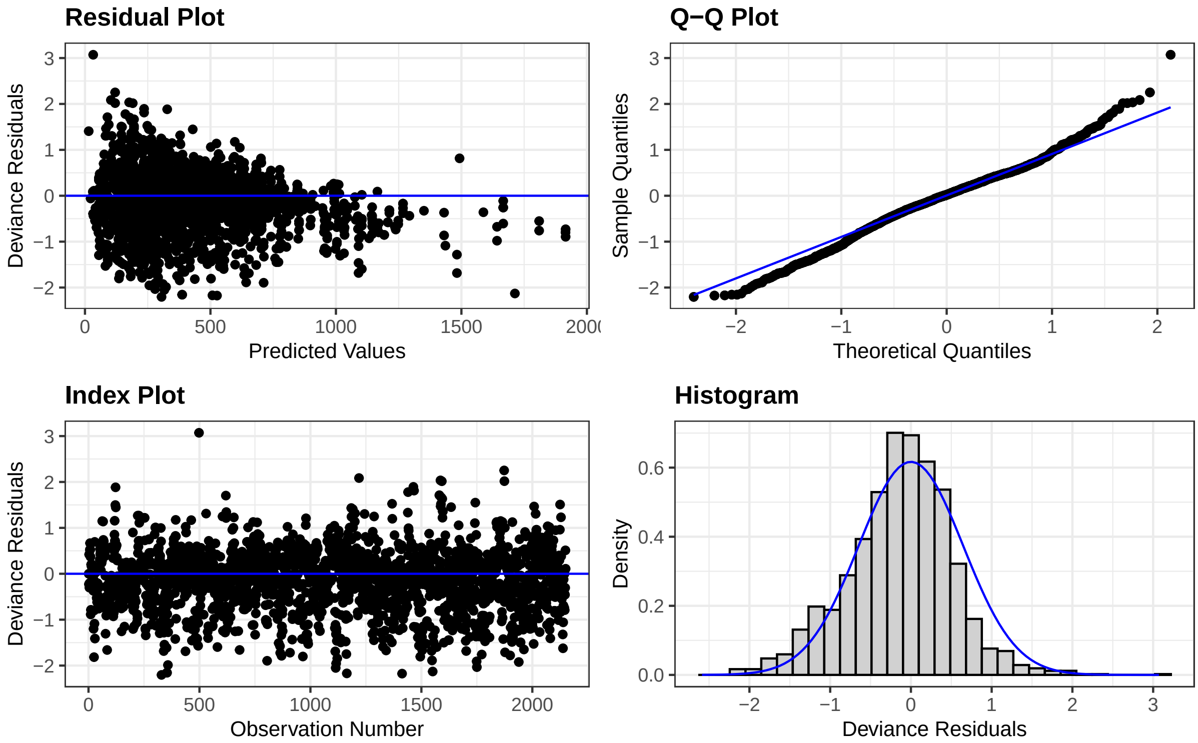


Figure A.2: Catch rate diagnostics for herrmanni curryfish. There were no influential standardised-residuals, beyond the values of -2 and 2

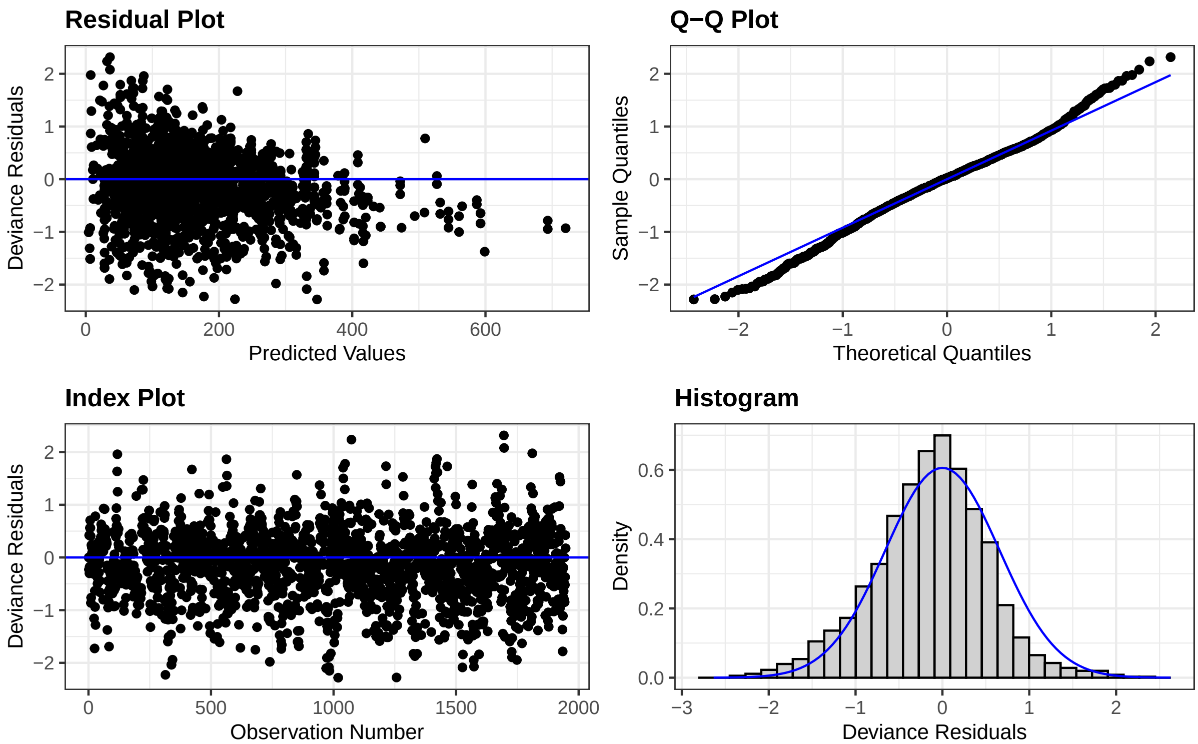


Figure A.3: Catch rate diagnostics for vastus curryfish. There were no influential standardised-residuals, beyond the values of -2 and 2.

A.2 Biological data

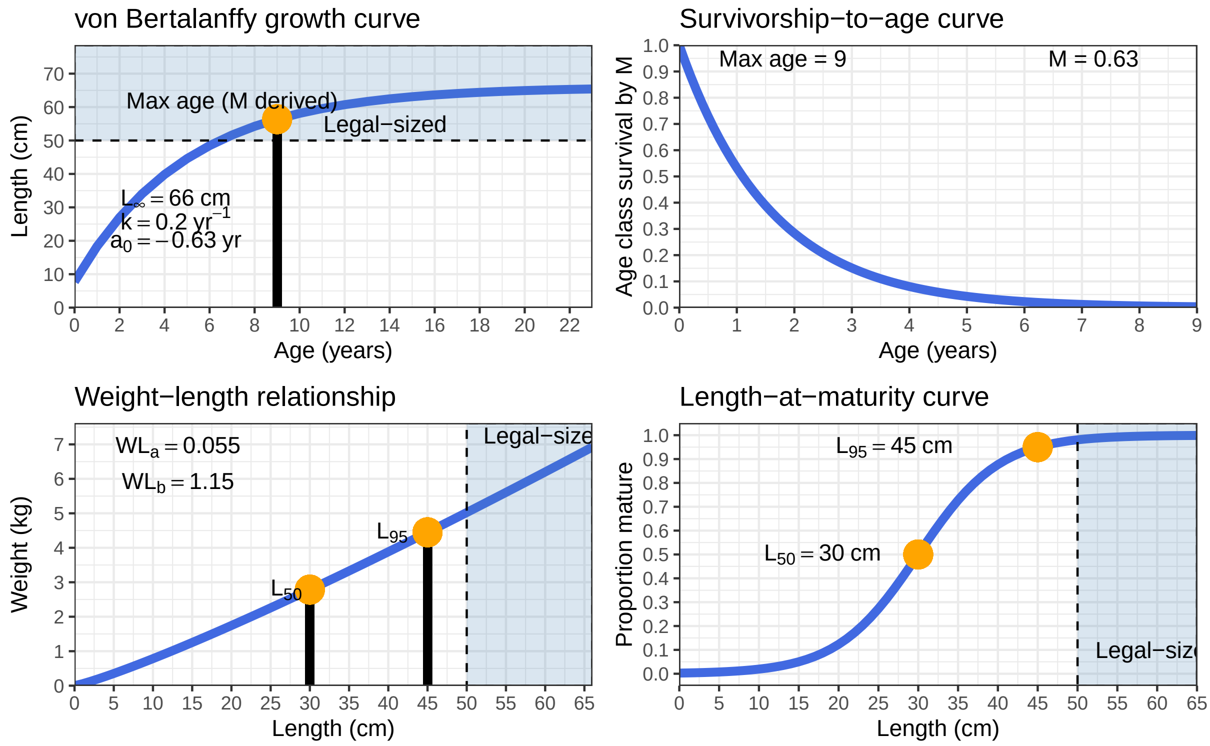


Figure A.4: Life history of prickly redfish.

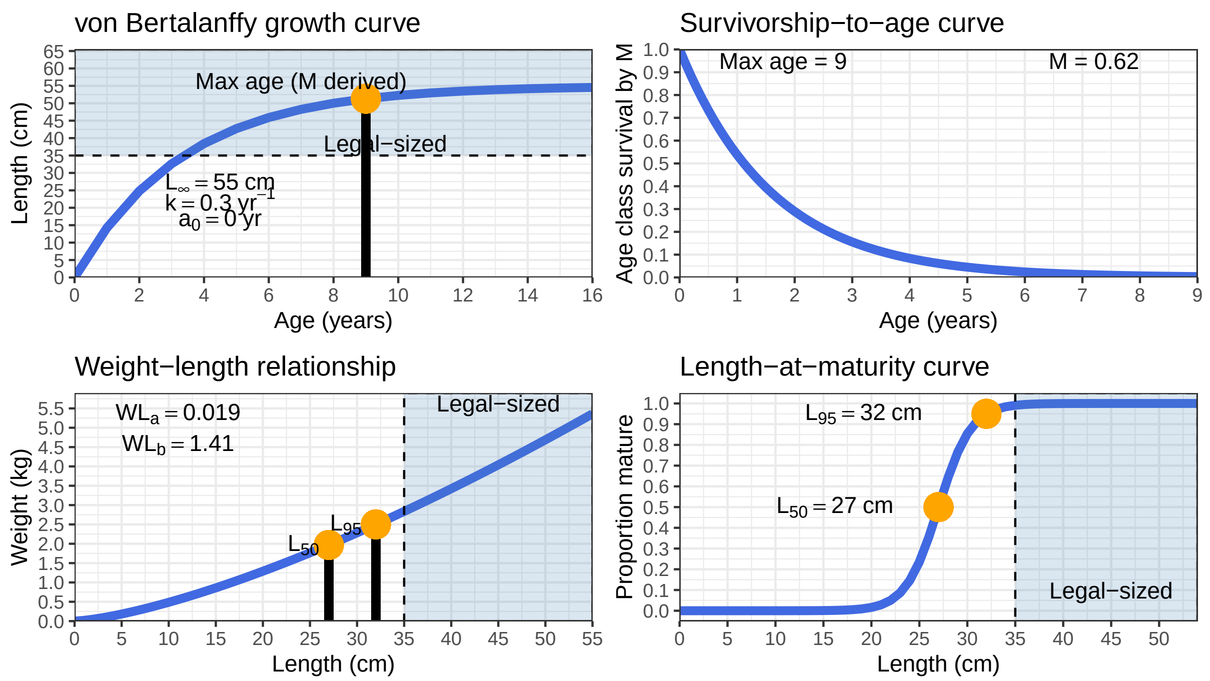


Figure A.5: Life history of hermanni curryfish.

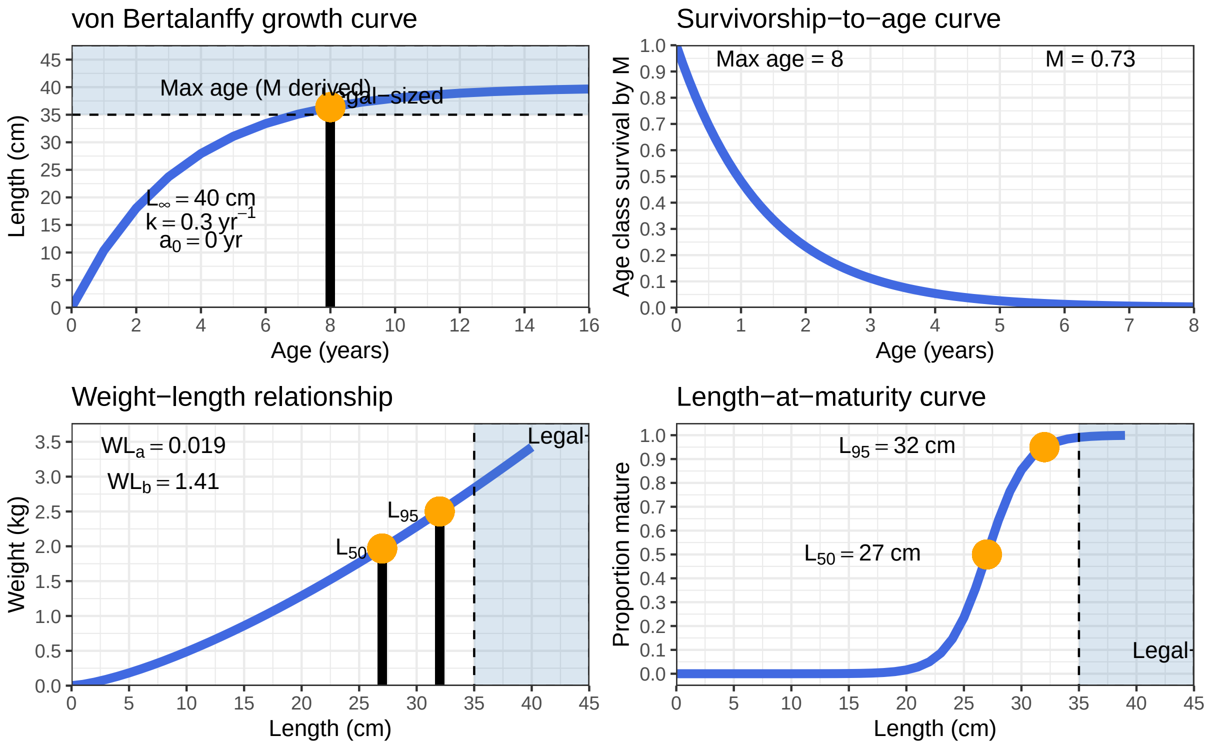


Figure A.6: Life history of vastus curryfish.

Appendix B Stock Synthesis base case outputs

This appendix provides results and outputs associated with the Stock Synthesis base case models that have not already been presented in the main body of the report.

B.1 Abundance indices

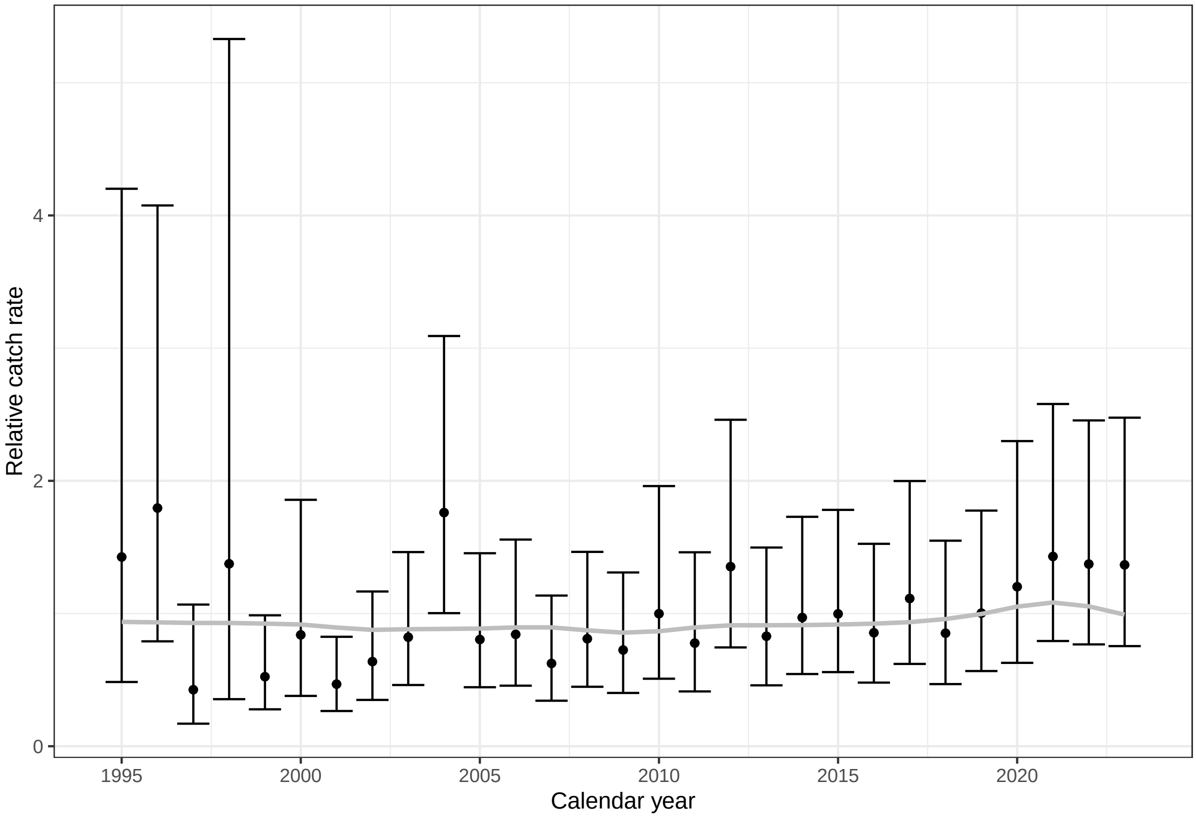


Figure B.1: Stock Synthesis base case model MLE estimates (grey line) of commercial catch rates for prickly redfish, from 1995 to 2023. Points and error bars represent the standardised cpue and error input to the model, relative to the mean.

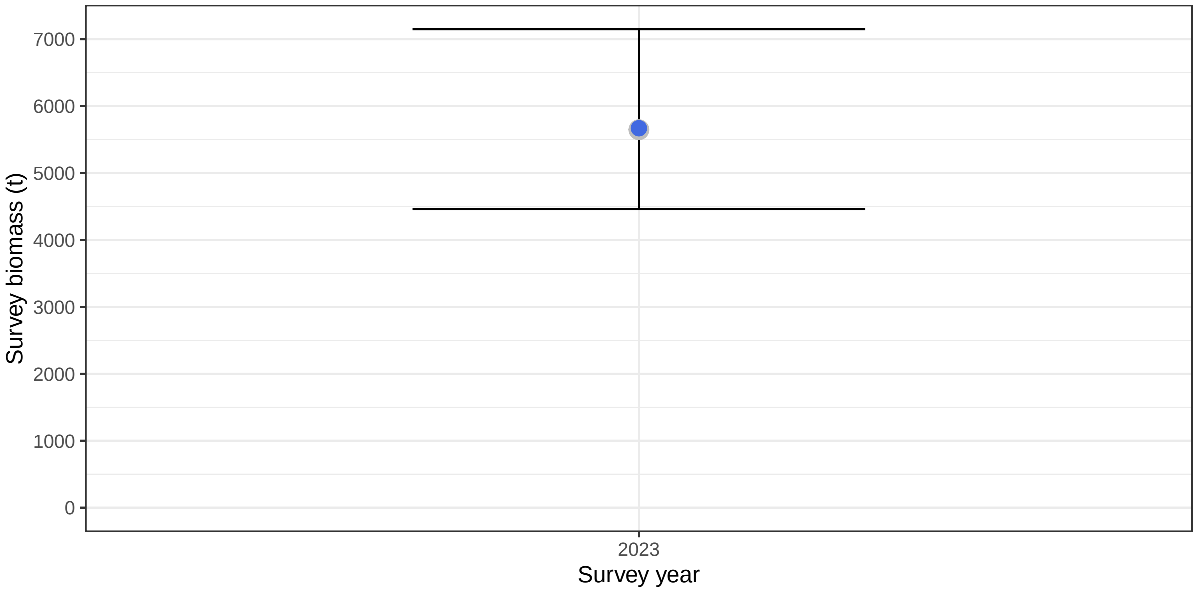


Figure B.2: Stock Synthesis model fit (blue dot) to survey estimated biomass (grey point with black error bars indicating the 95 percent CI of the estimate) for prickly redfish.

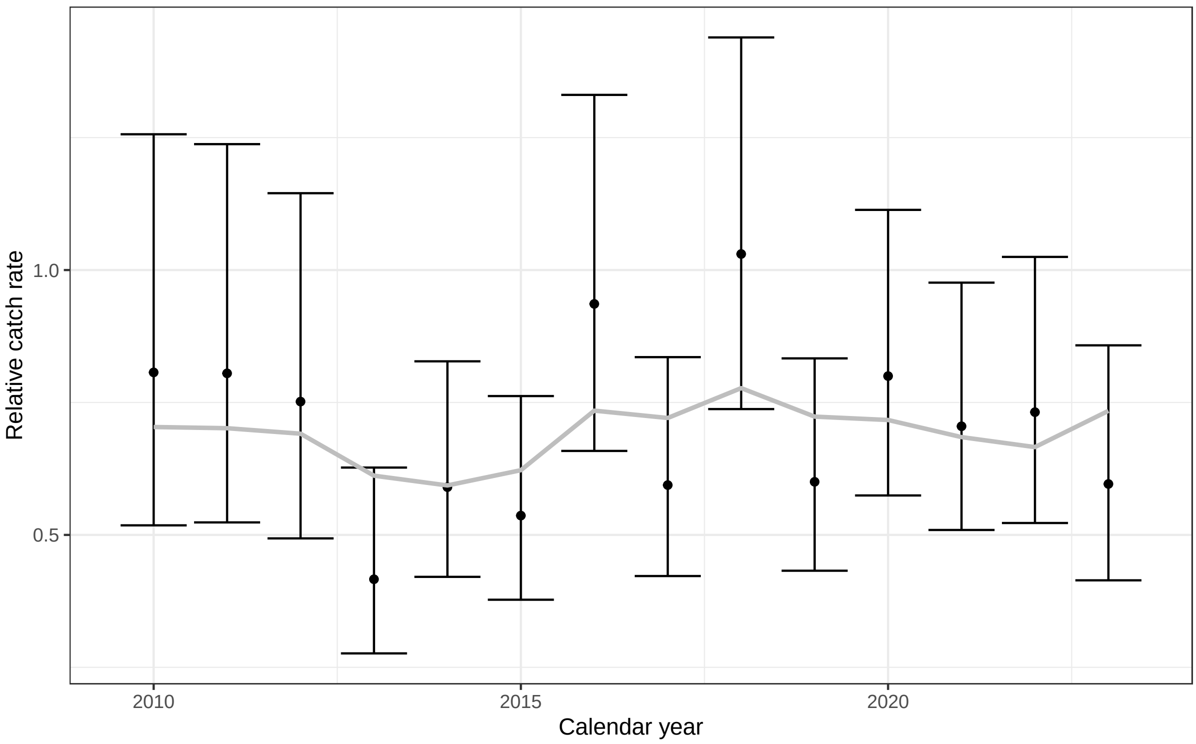


Figure B.3: Stock Synthesis base case model MLE estimates (grey line) of commercial catch rates for herrmanni curryfish, from 2010 to 2023. Points and error bars represent the standardised cpue and error input to the model, relative to the mean.

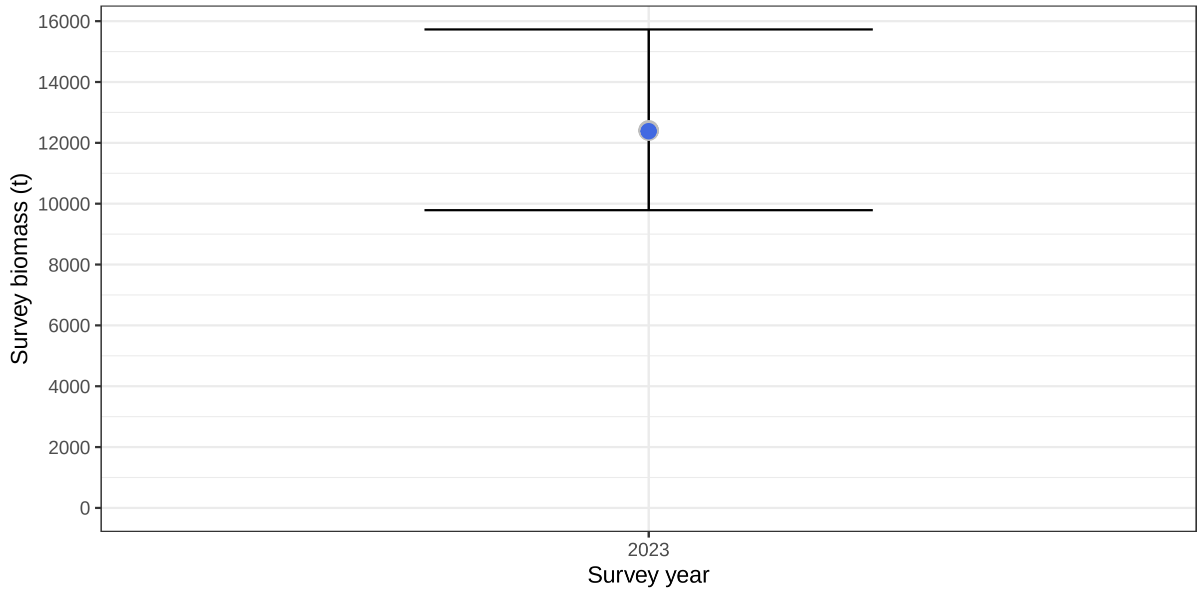


Figure B.4: Stock Synthesis model fit (blue dot) to survey estimated biomass (grey point with black error bars indicating the 95 percent CI of the estimate) for herrmanni curryfish.

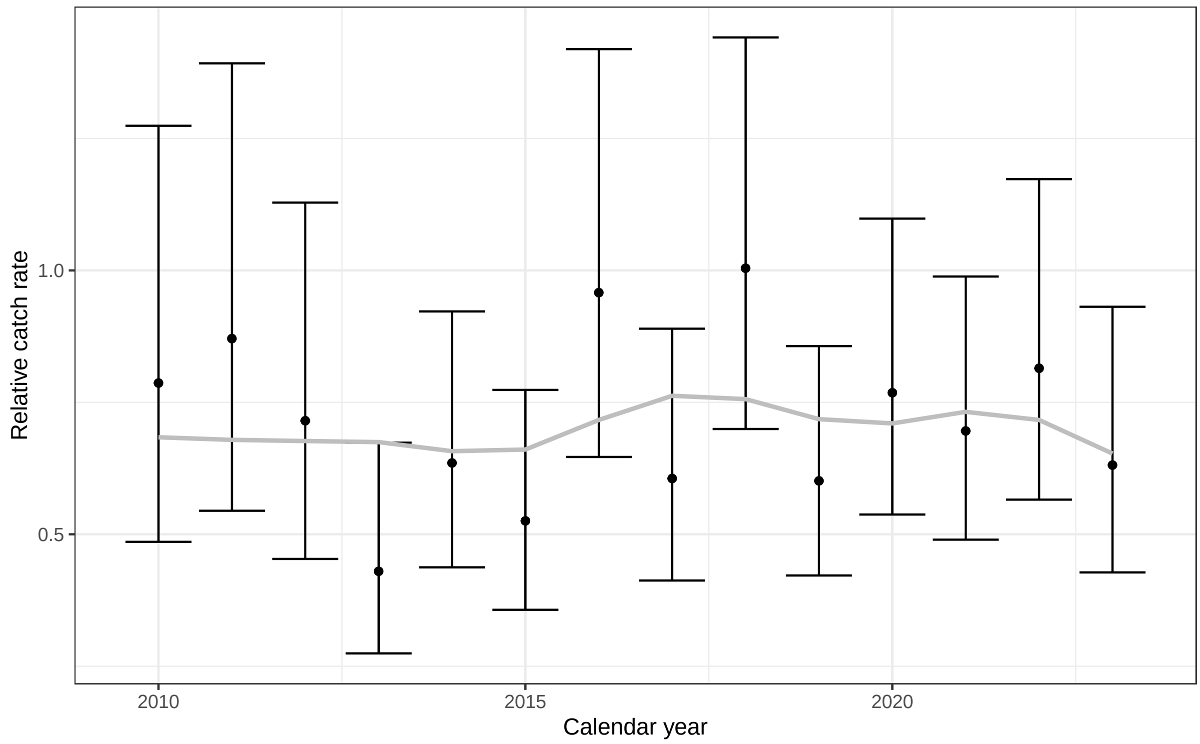


Figure B.5: Stock Synthesis base case model MLE estimates (grey line) of commercial catch rates for vastus curryfish, from 2010 to 2023. Points and error bars represent the standardised cpue and error input to the model, relative to the mean.

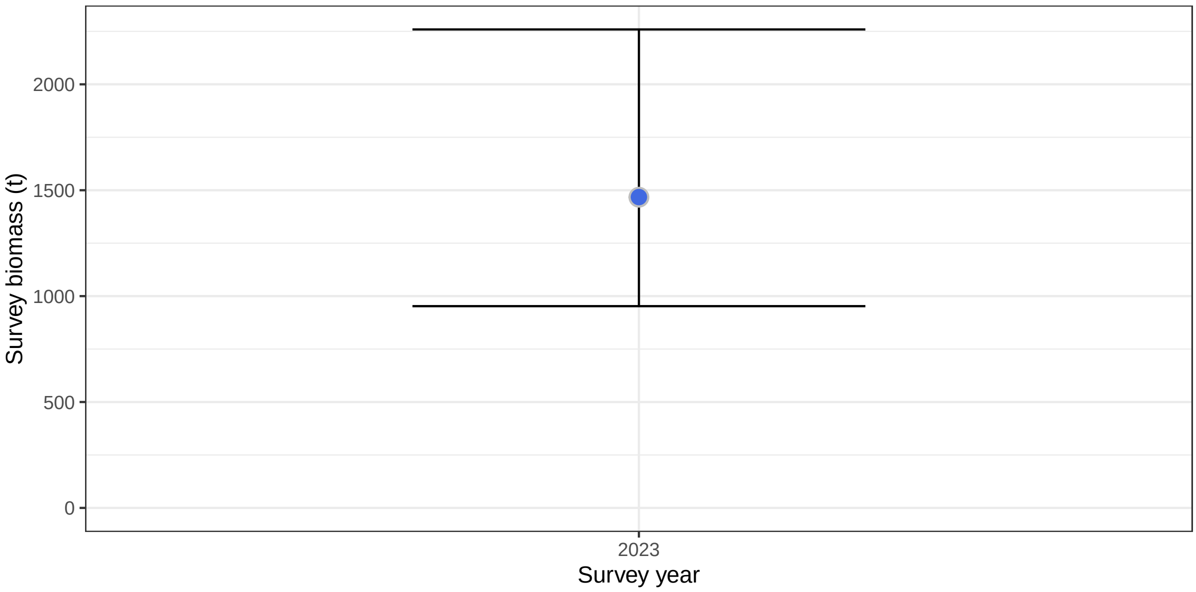


Figure B.6: Stock Synthesis model fit (blue dot) to survey estimated biomass (grey point with black error bars indicating the 95 percent CI of the estimate) for vastus curryfish.

B.2 Length composition

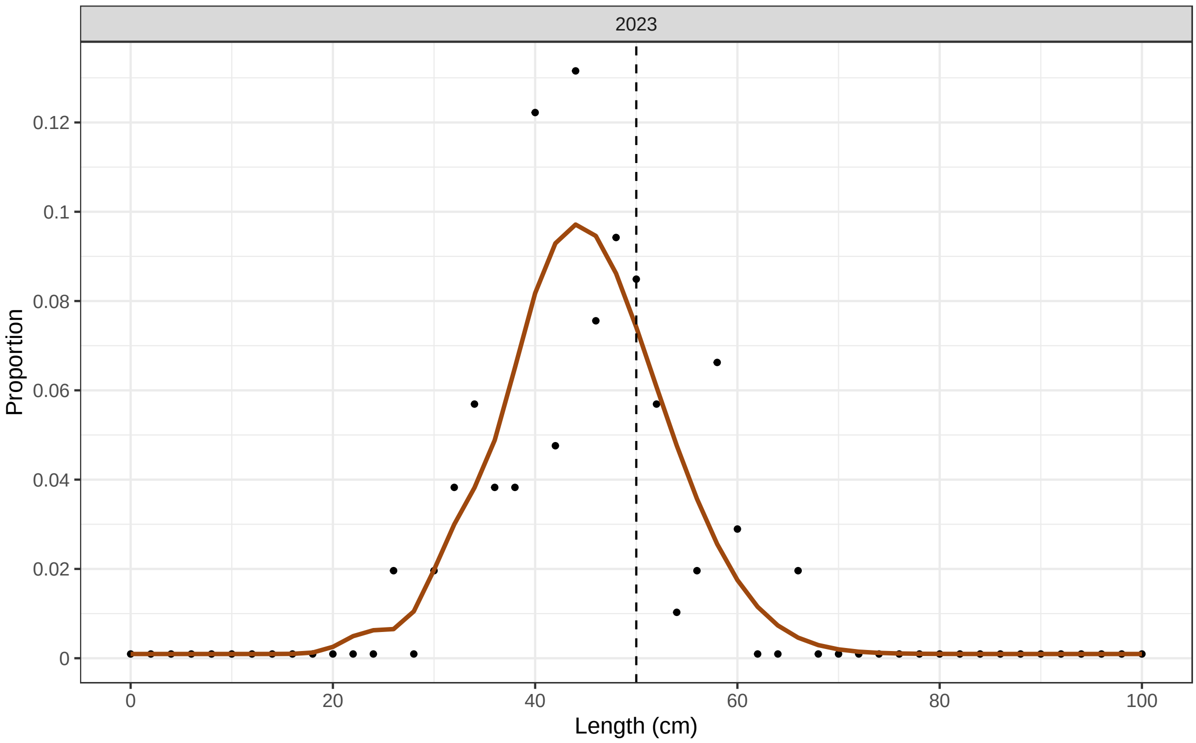


Figure B.7: Stock Synthesis model fits (brown line) to length structures for the 2023 survey for prickly redfish. The dashed vertical line indicates the MLS of 50 cm.

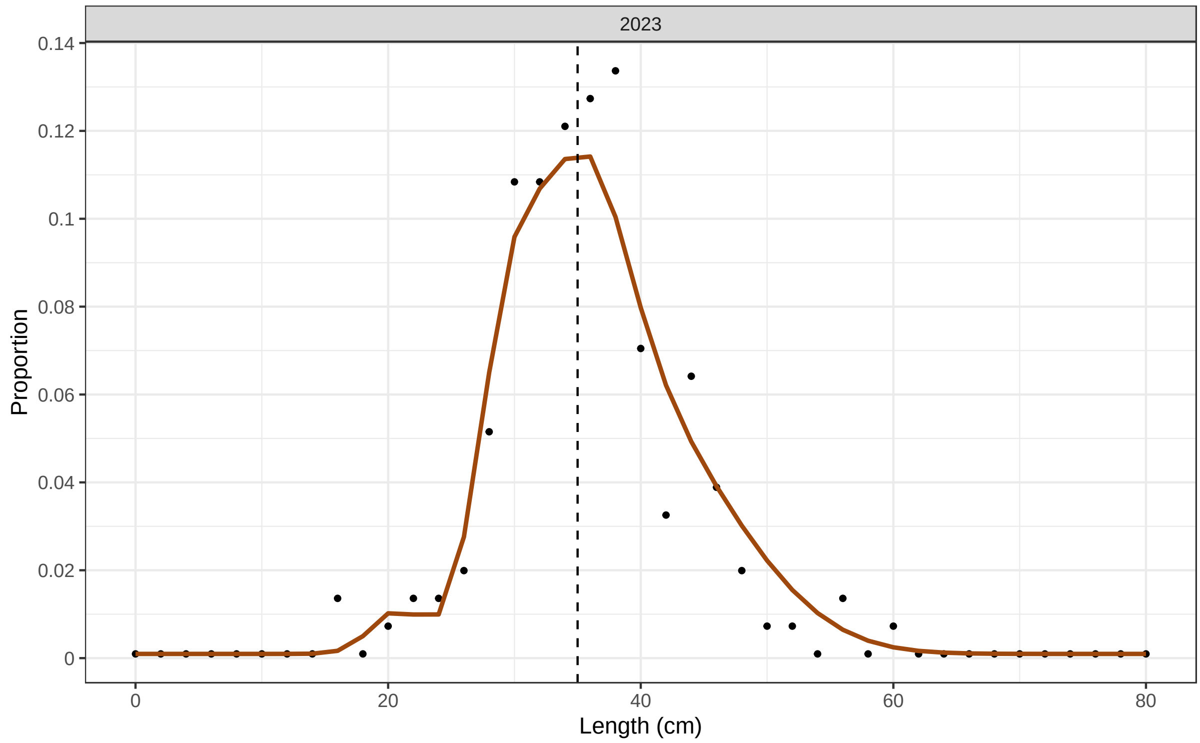


Figure B.8: Stock Synthesis model fits (brown line) to length structures for the 2023 survey for herrmanni curryfish. The dashed vertical line indicates the MLS of 35 cm.

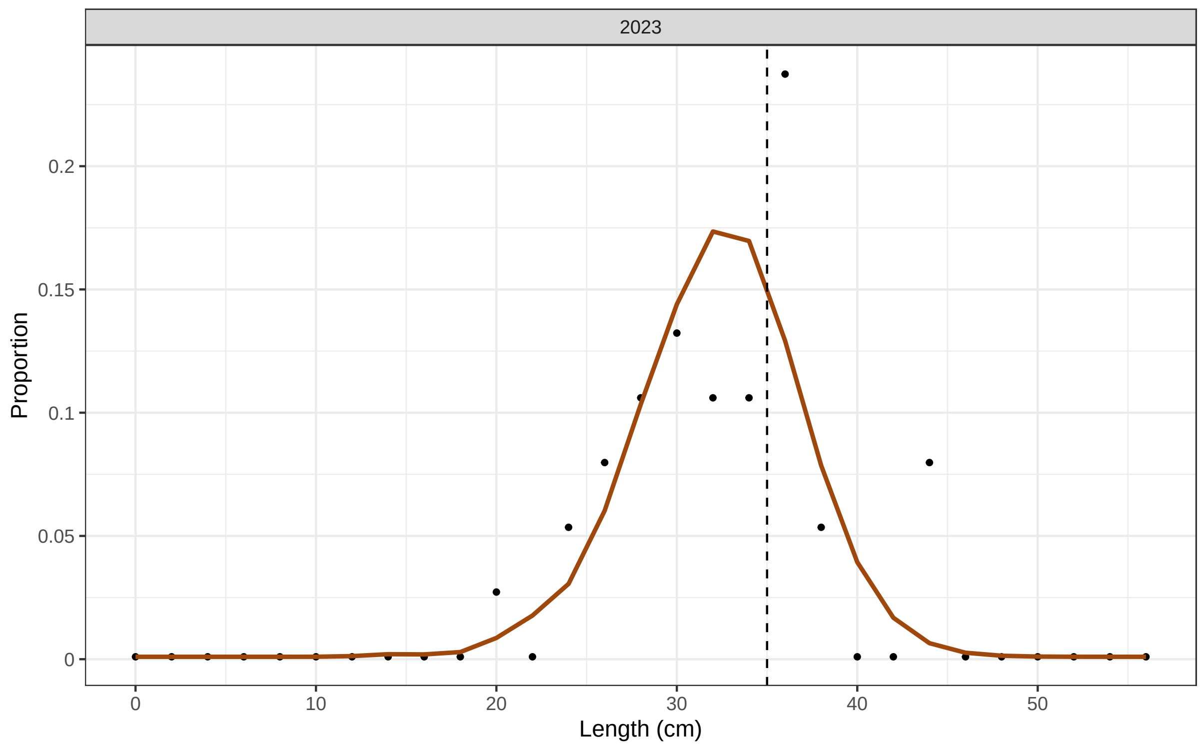


Figure B.9: Stock Synthesis model fits (brown line) to length structures for the 2023 survey for vastus curryfish. The dashed vertical line indicates the MLS of 35 cm.

B.3 Stock-recruit curve

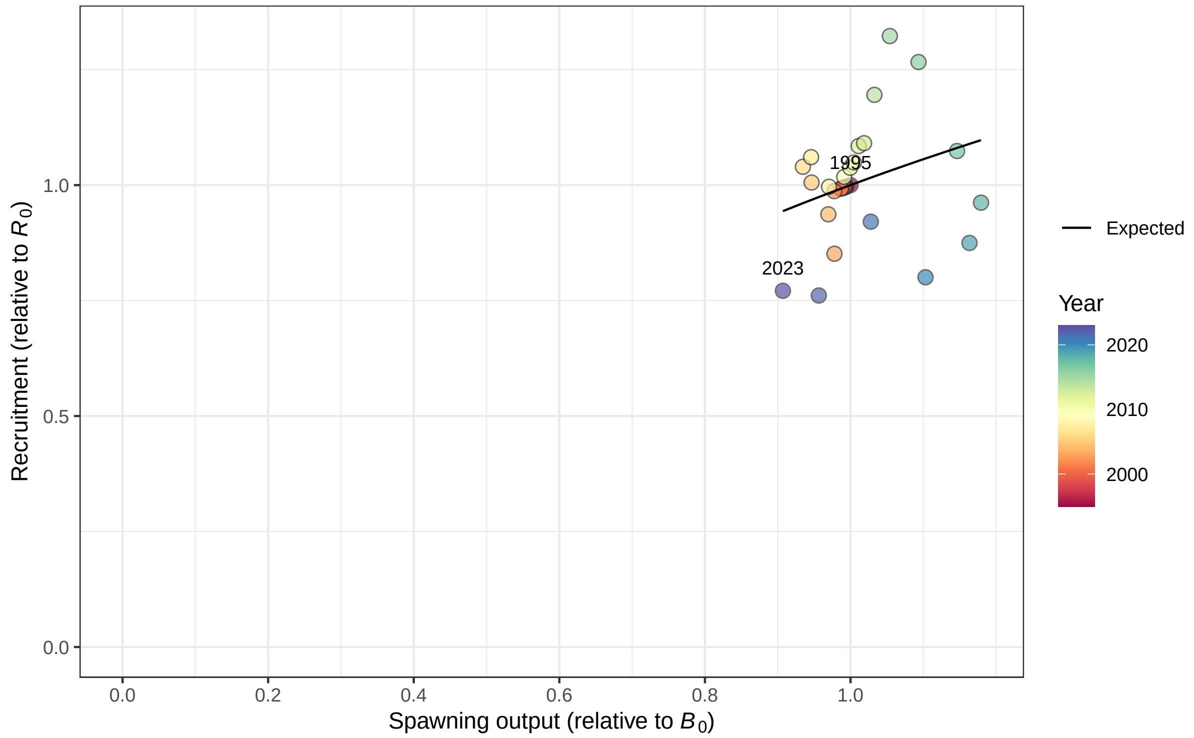


Figure B.10: Stock-recruitment curve estimated via Stock Synthesis MLE for prickly redfish. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

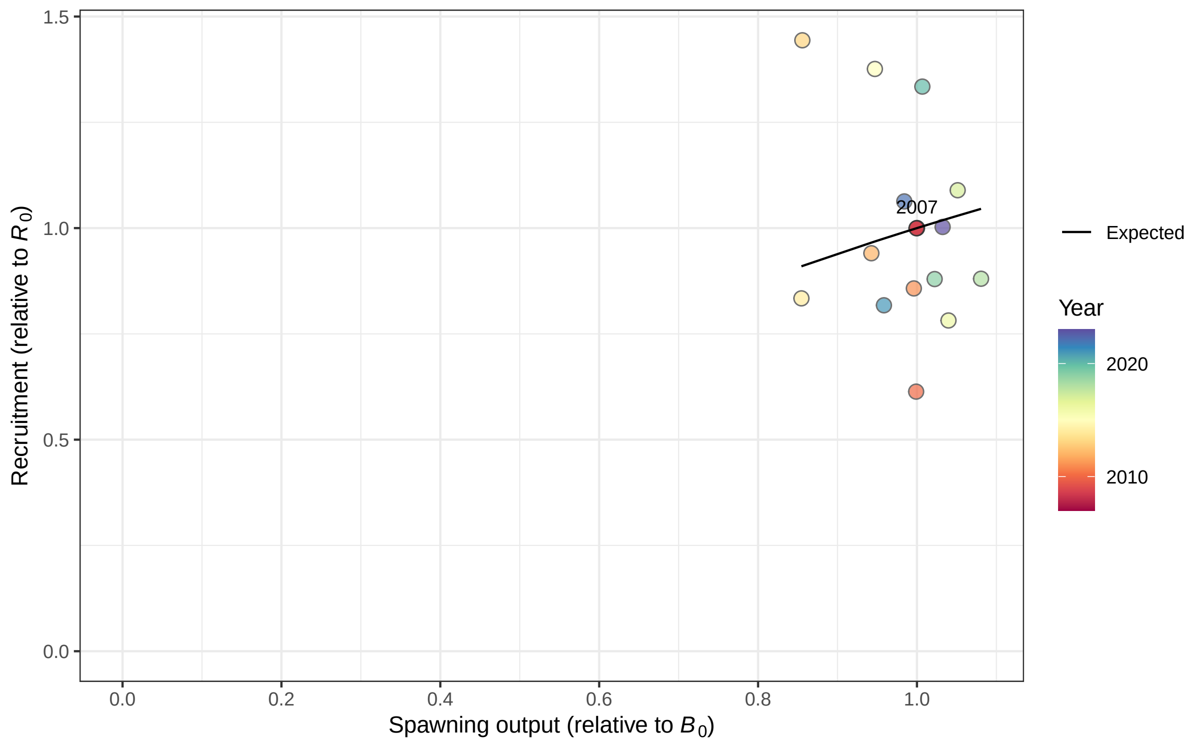


Figure B.11: Stock-recruitment curve estimated via Stock Synthesis MLE for herrmanni curryfish. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

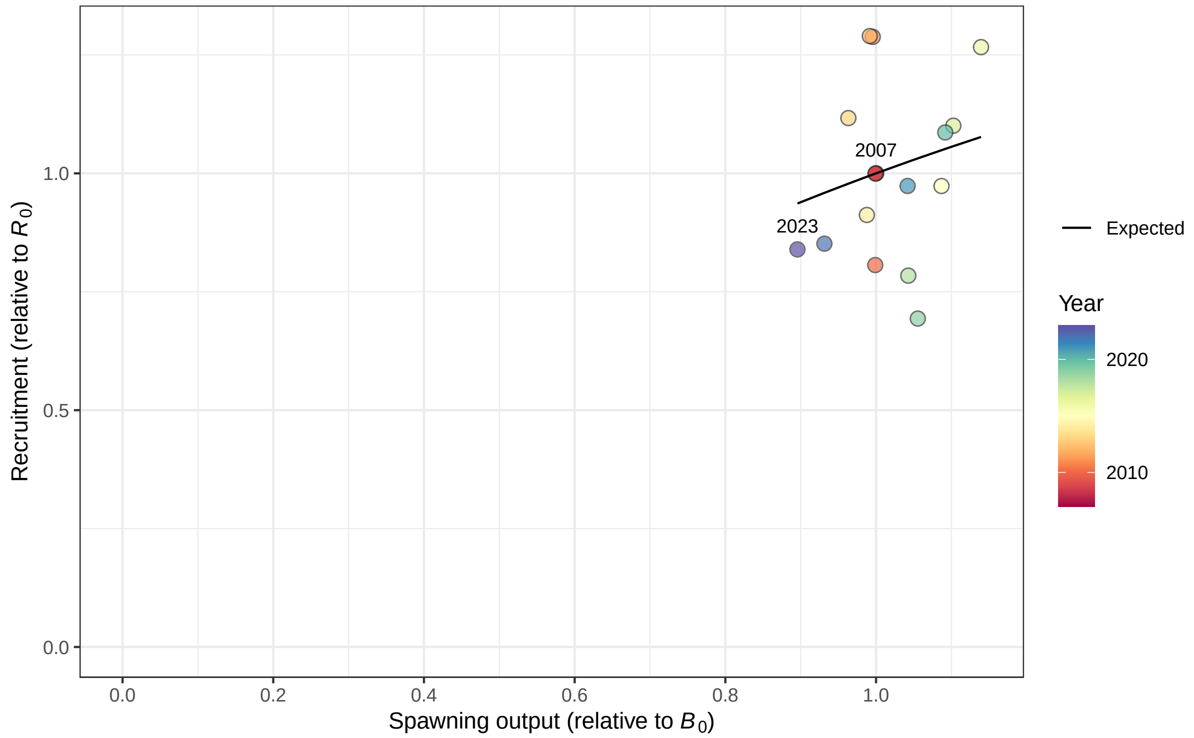


Figure B.12: Stock-recruitment curve estimated via Stock Synthesis MLE for vastus curryfish. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

B.4 Recruitment deviations

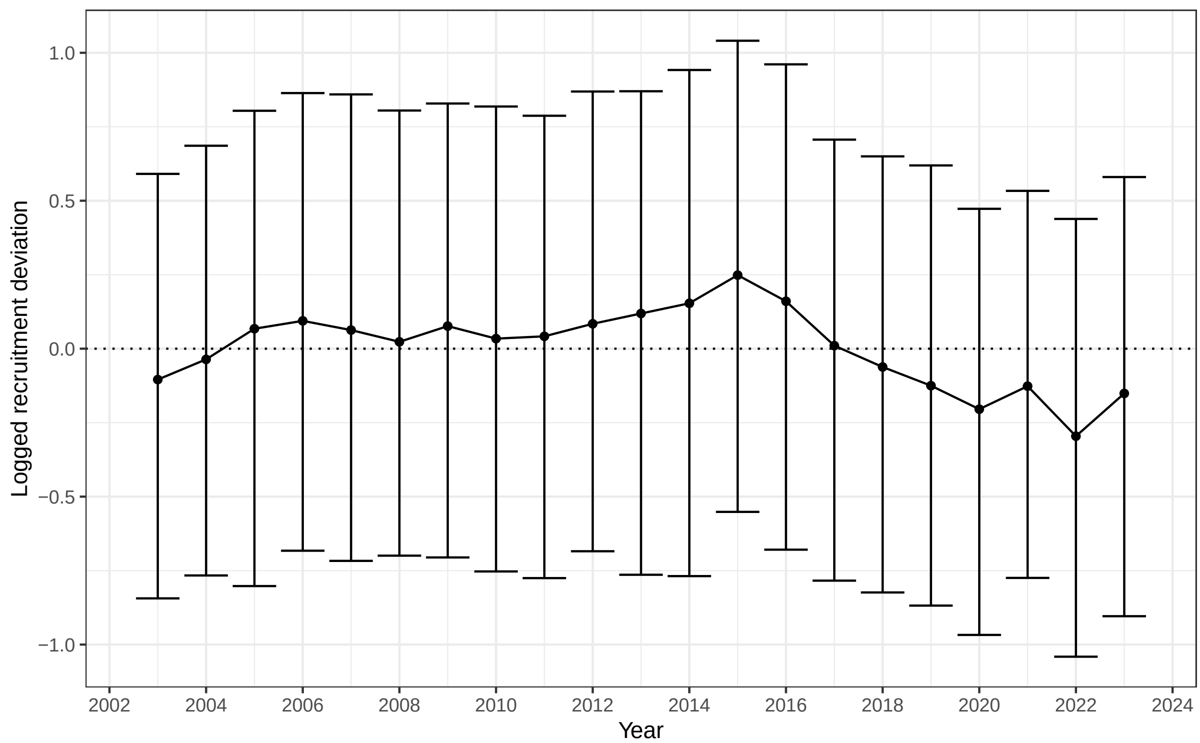


Figure B.13: Recruitment deviations (Stock Synthesis MCMC posterior medians) for prickly redfish, from 2003 to 2023.

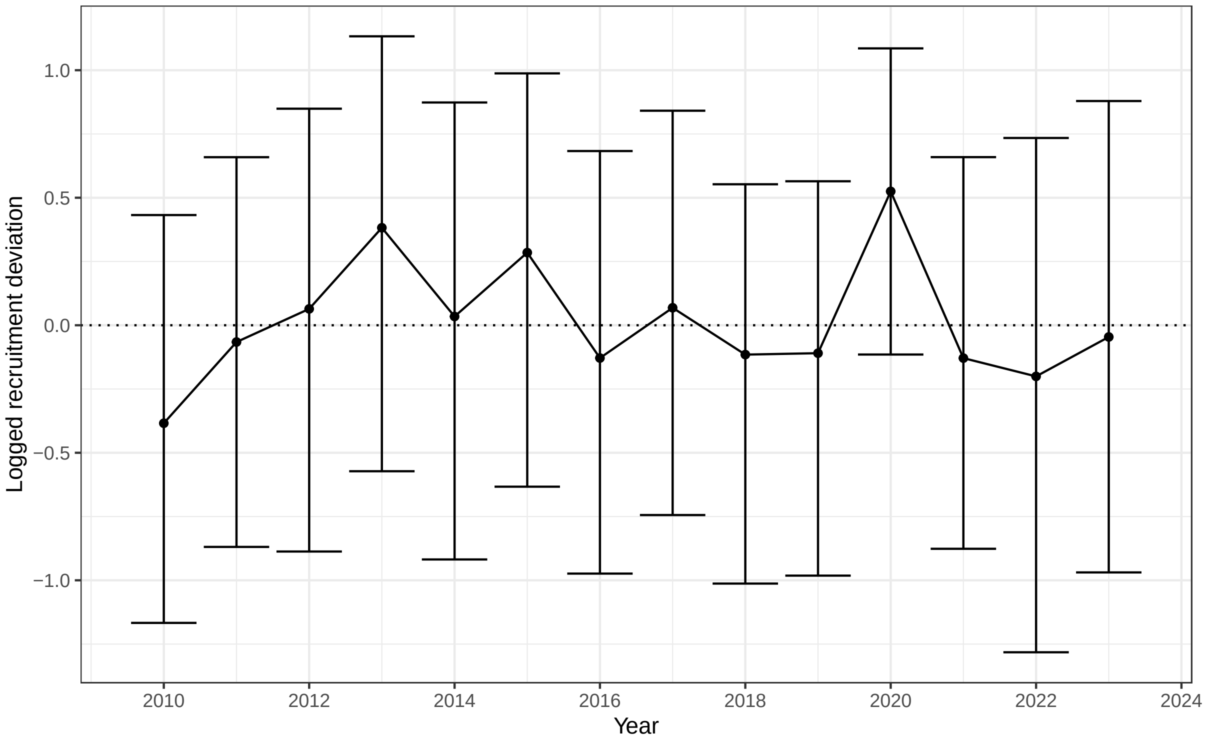


Figure B.14: Recruitment deviations (Stock Synthesis MCMC posterior medians) for herrmanni curryfish, from 2010 to 2023.

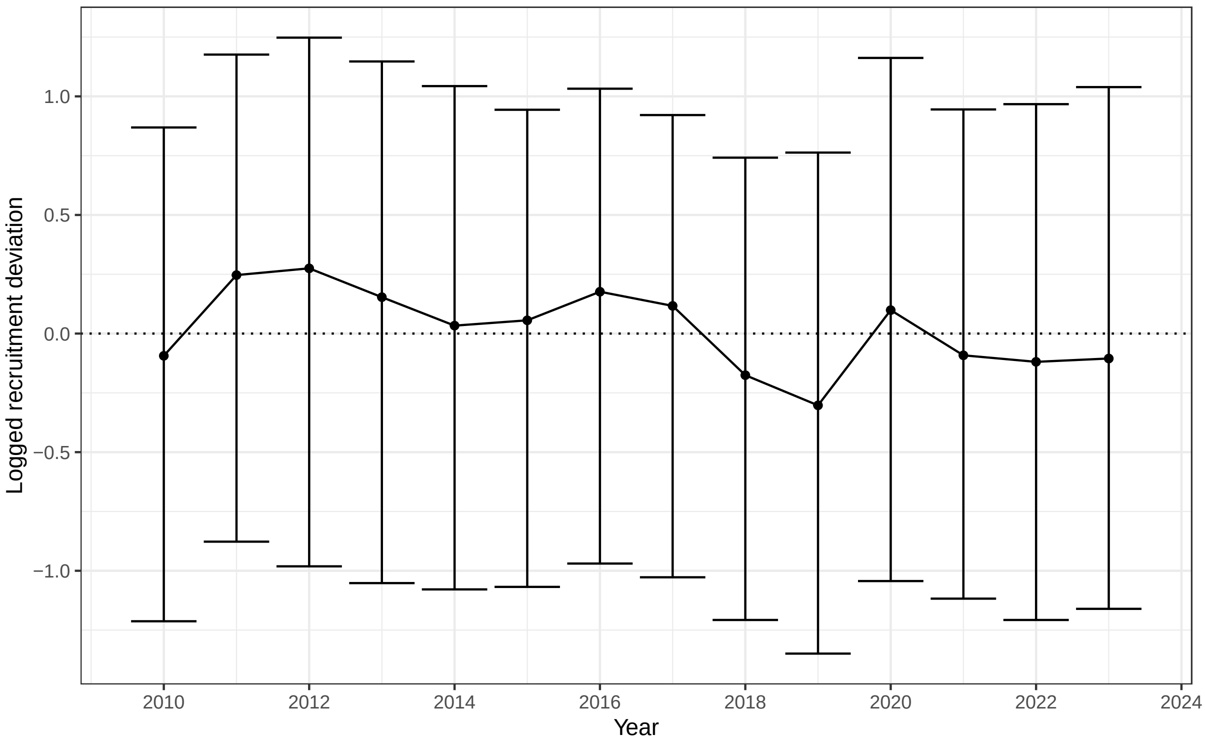


Figure B.15: Recruitment deviations (Stock Synthesis MCMC posterior medians) for vastus curryfish, from 2010 to 2023.

B.5 Fishing mortality

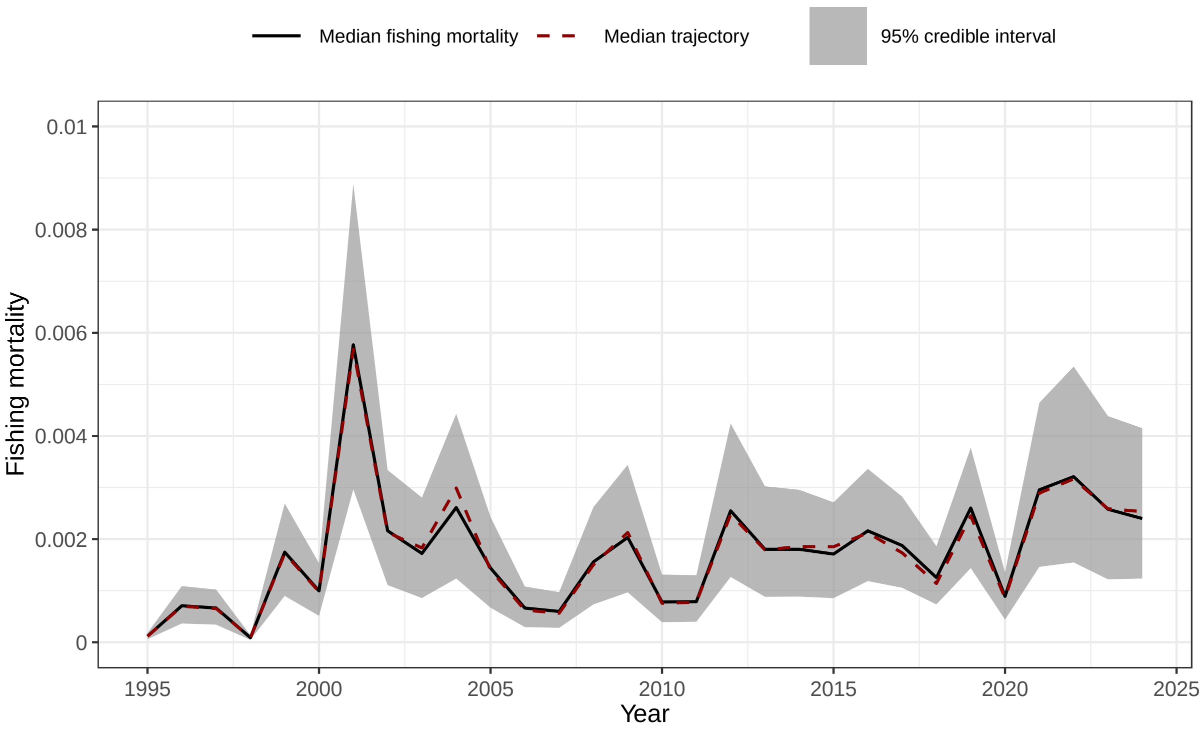


Figure B.16: Predicted legal-sized F from Stock Synthesis MCMC and MLE for prickly redfish, from 1995 to 2023.

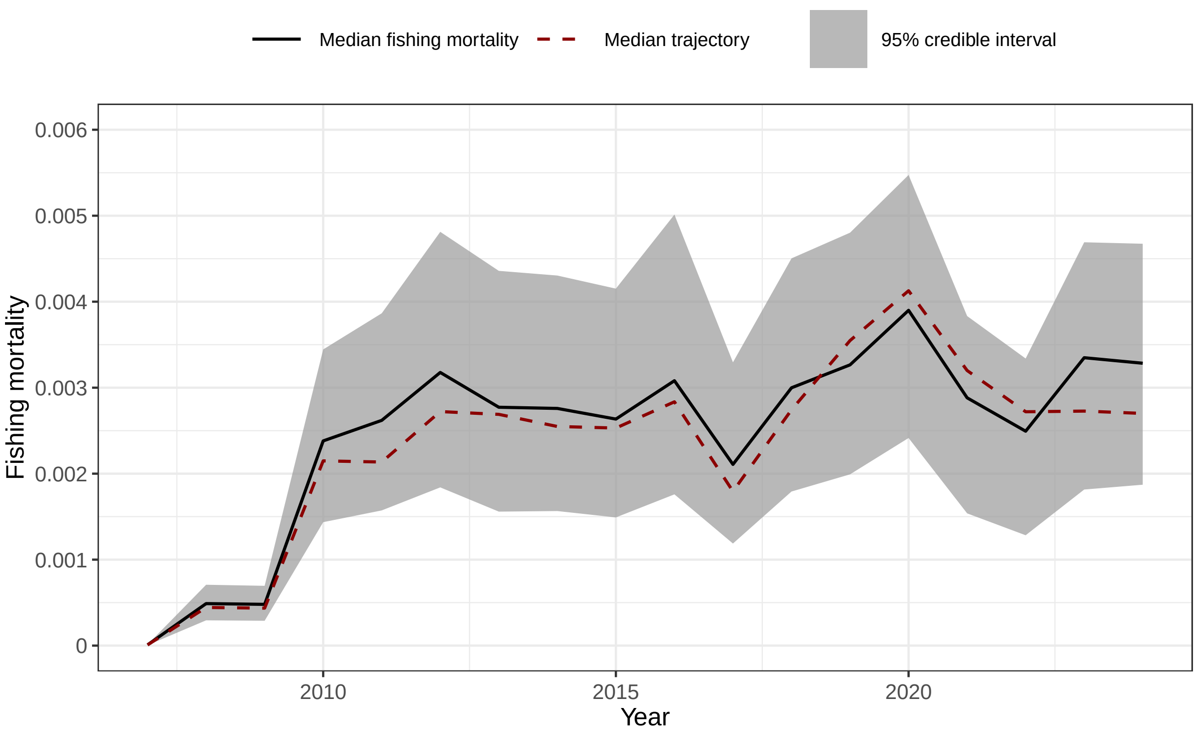


Figure B.17: Predicted legal-sized F from Stock Synthesis MCMC and MLE for herrmanni curryfish, from 2007 to 2023.

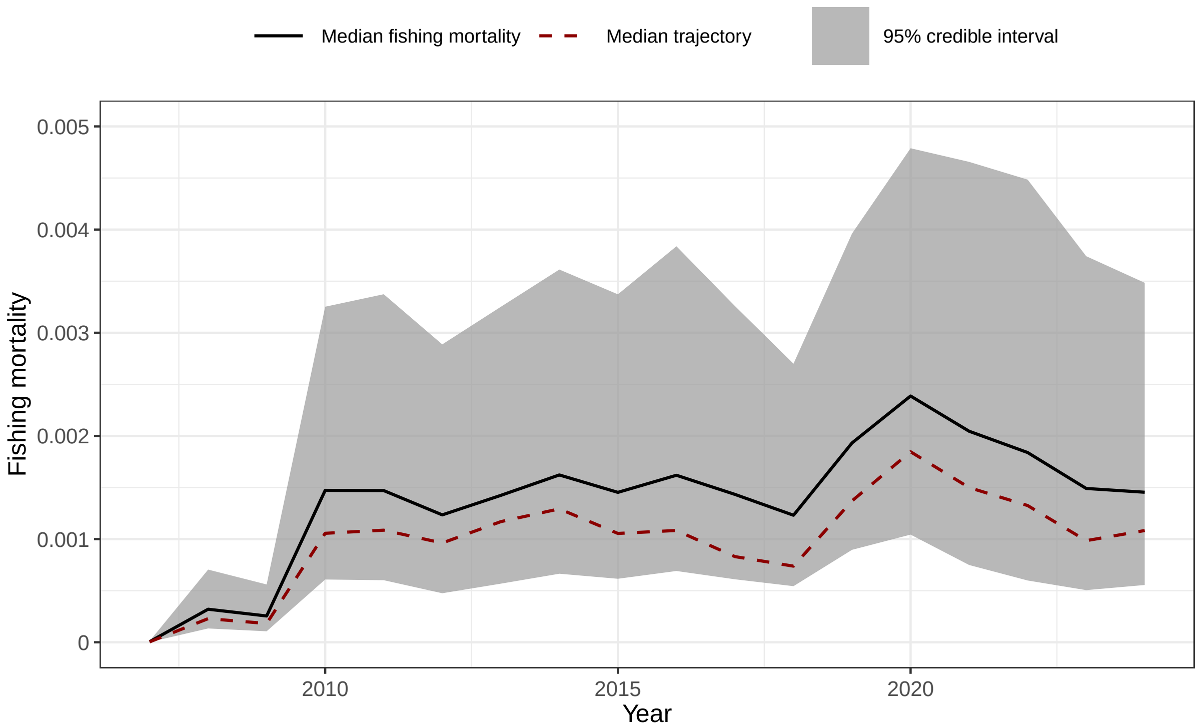


Figure B.18: Predicted legal-sized F from Stock Synthesis MCMC and MLE for vastus curryfish, from 2007 to 2023.

Appendix C DDUST base case outputs

C.1 Biomass

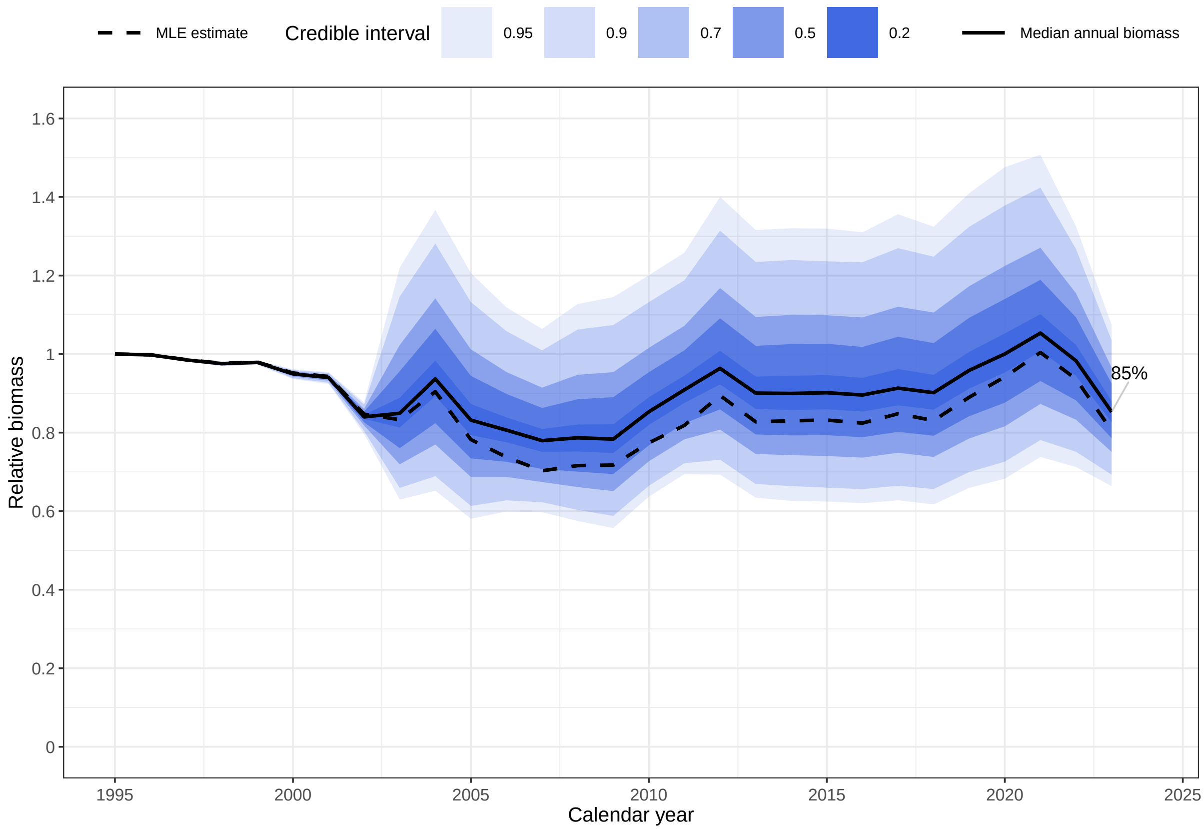


Figure C.1: MCMC predicted biomass trajectory relative to unfished from the DDUST model for prickly redfish, from 1995 to 2023. Blue shading indicates the biomass Bayesian credibility interval.

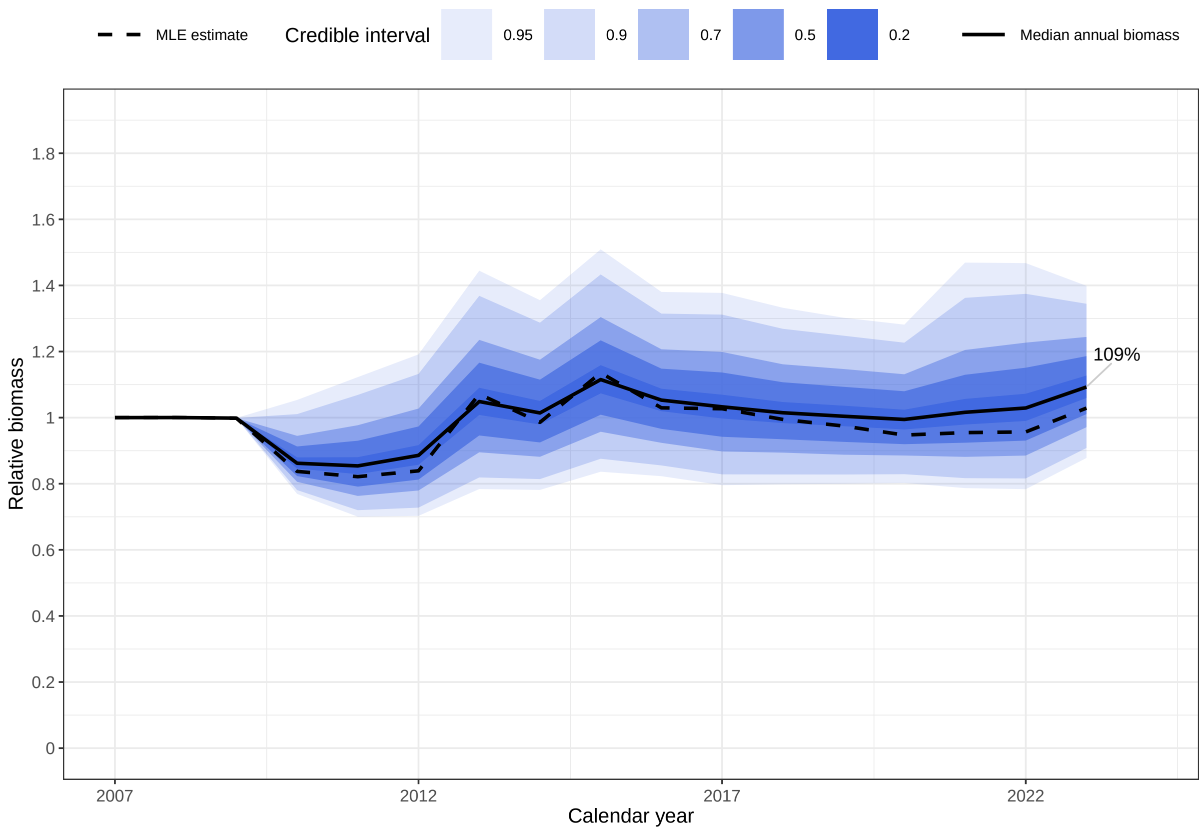


Figure C.2: MCMC predicted biomass trajectory relative to unfished from the DDUST model for herrmanni curryfish, from 2007 to 2023. Blue shading indicates the biomass Bayesian credibility interval.

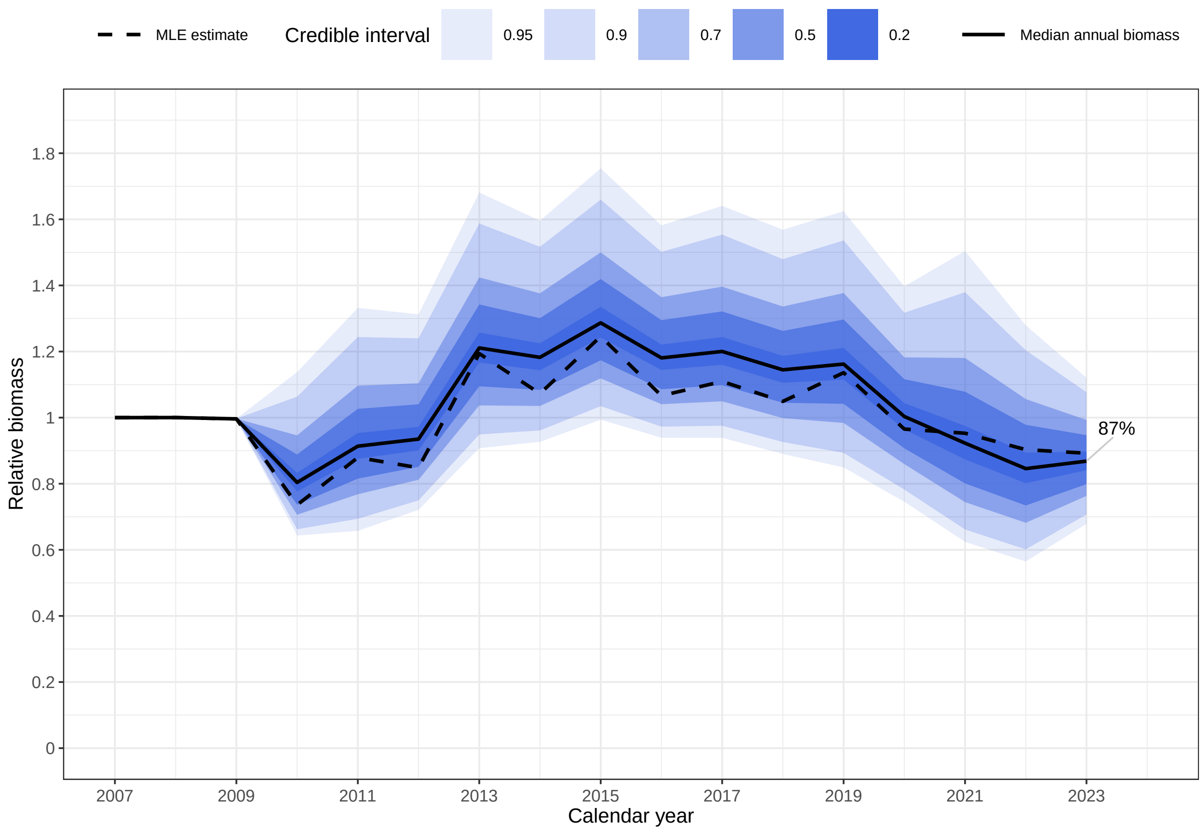


Figure C.3: MCMC predicted biomass trajectory relative to unfished from the DDUST model for vastus curryfish, from 2007 to 2023. Blue shading indicates the biomass Bayesian credibility interval.

C.2 Abundance indices

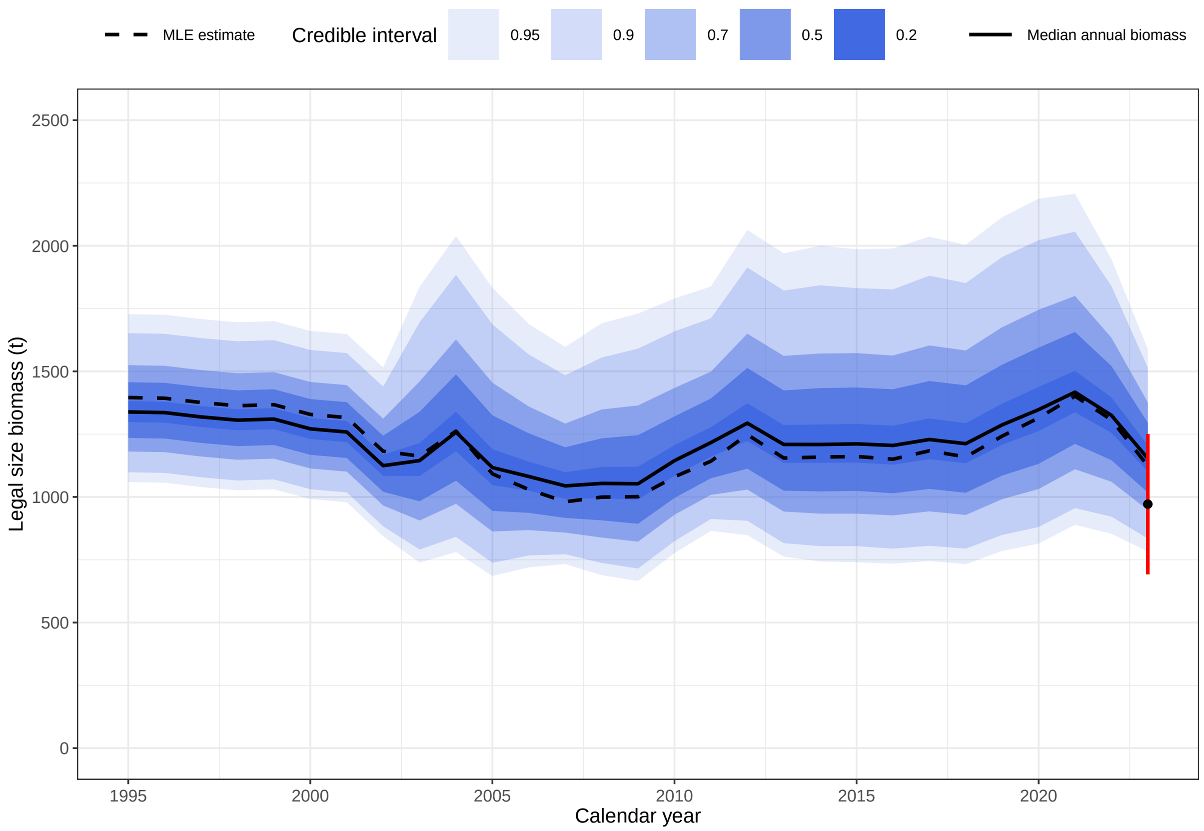


Figure C.4: DDUST model fits to legal-sized biomass survey estimate (black point with red error bars indicating the sd of the estimate) for prickly redfish, from 1995 to 2023.

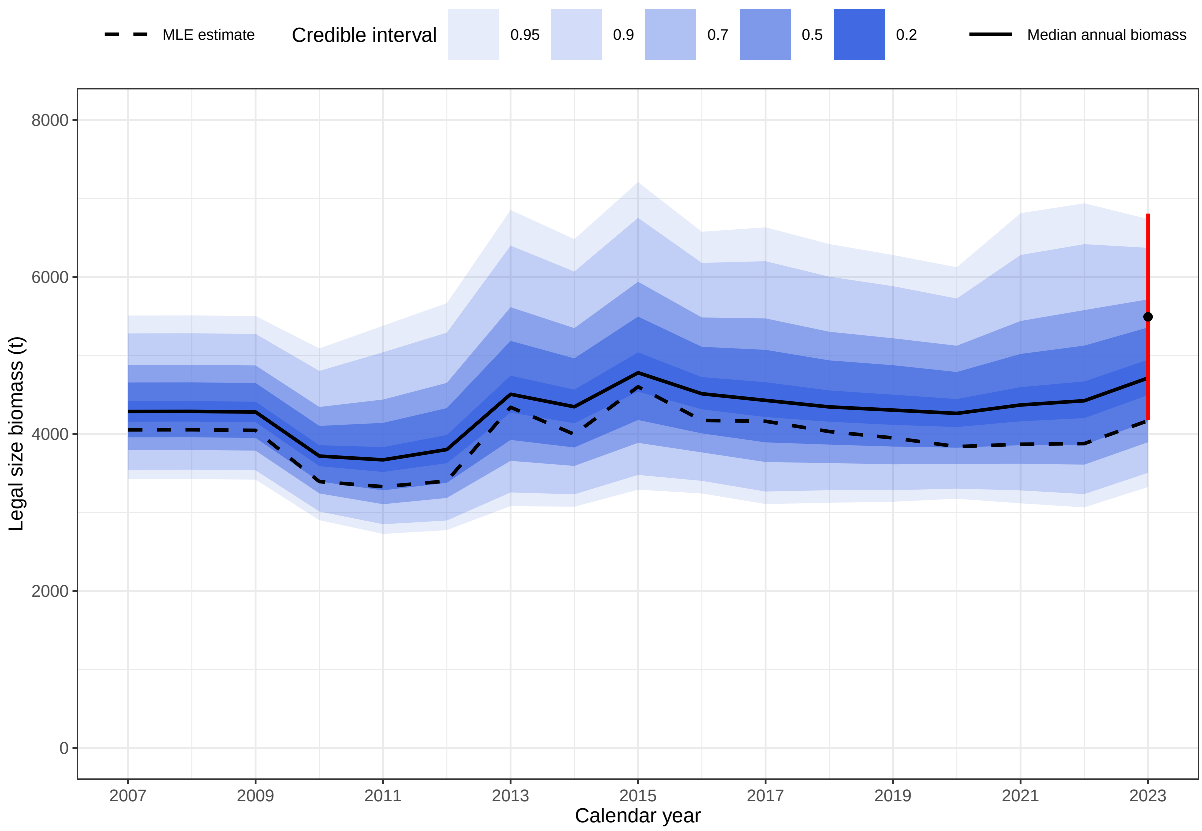


Figure C.5: DDUST model fits to legal-sized biomass survey estimate (black point with red error bars indicating the sd of the estimate) for herrmanni curryfish, from 2007 to 2023.

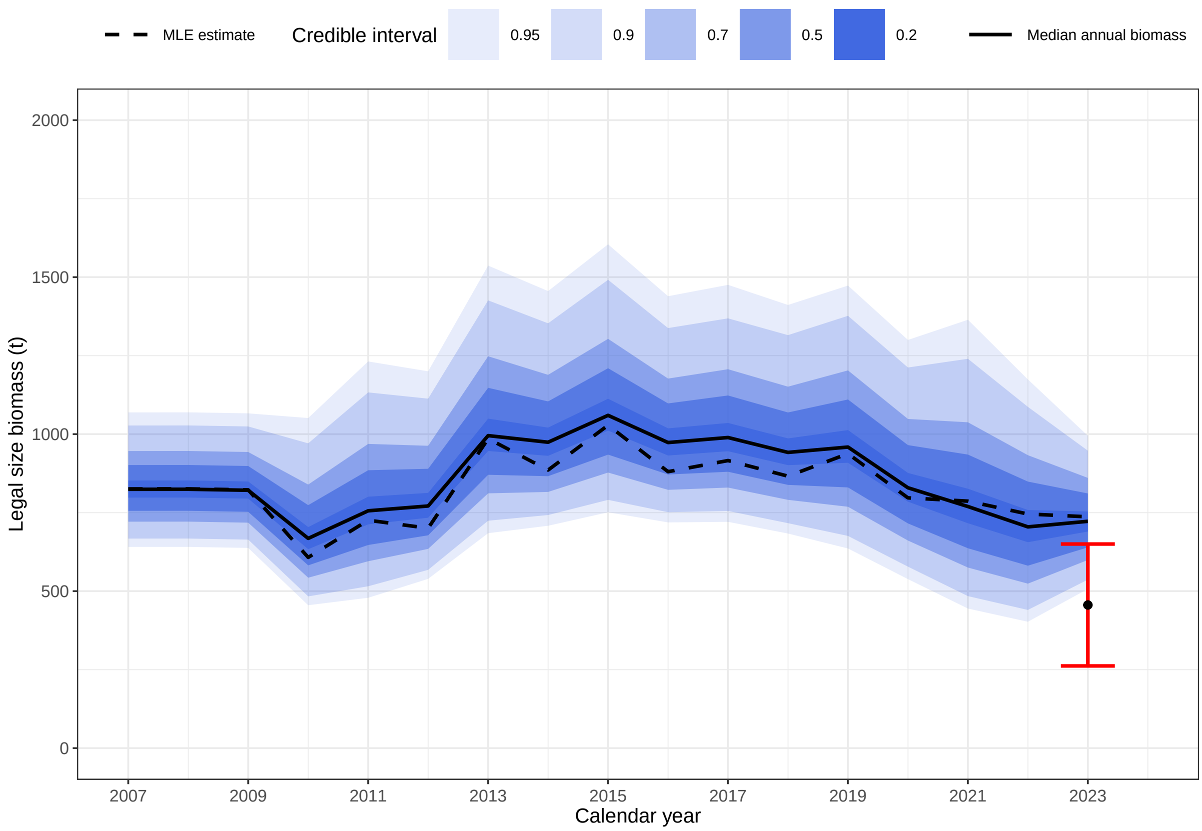


Figure C.6: DDUST model fits to legal-sized biomass survey estimate (black point with red error bars indicating the sd of the estimate) for vastus curryfish, from 2007 to 2023.

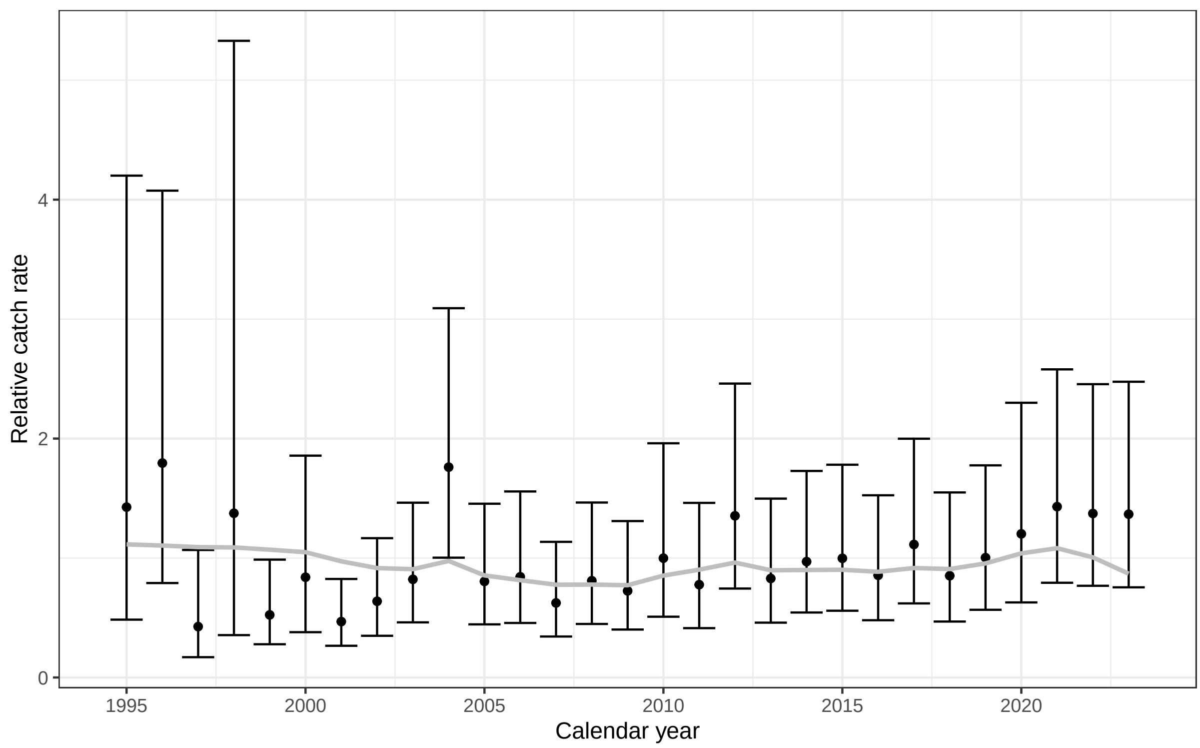


Figure C.7: DDUST model MLE estimates of commercial catch rates for prickly redfish, from 1995 to 2023.

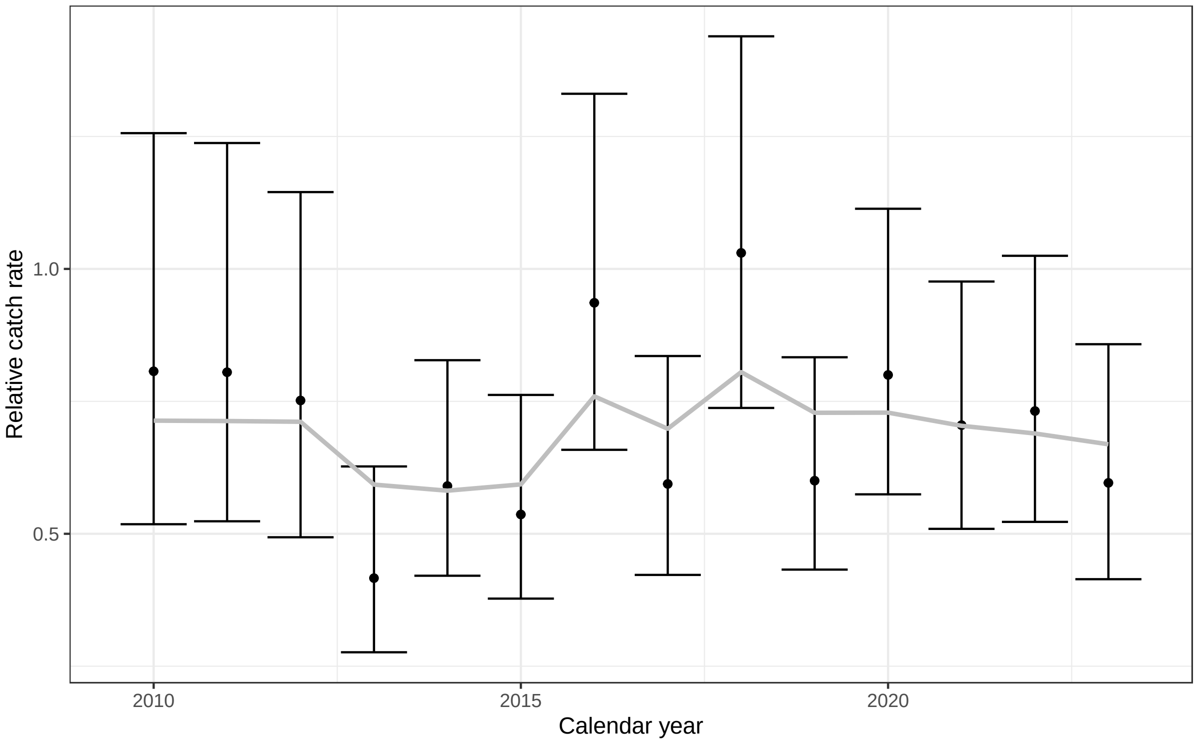


Figure C.8: DDUST model MLE estimates of commercial catch rates for herrmanni curryfish, from 2010 to 2023.

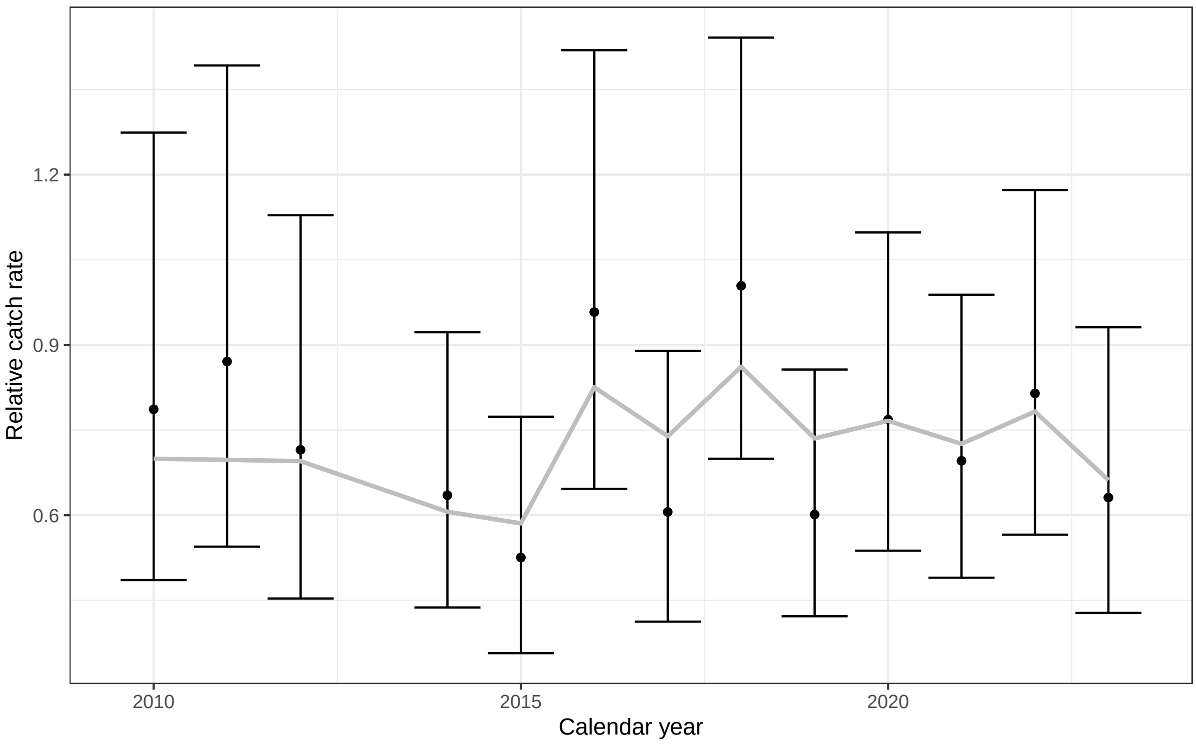


Figure C.9: DDUST model MLE estimates of commercial catch rates for vastus curryfish, from 2010 to 2023.

C.3 Stock-recruit curve

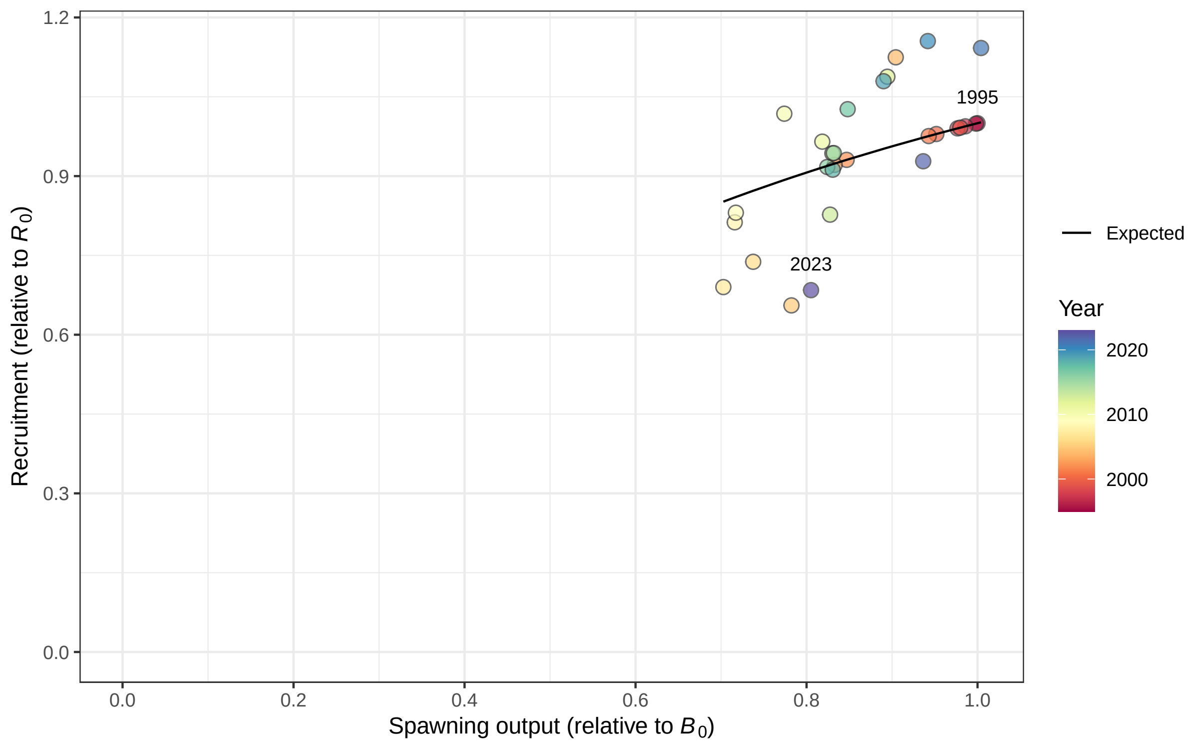


Figure C.10: Stock-recruitment curve estimated via MLE for prickly redfish. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

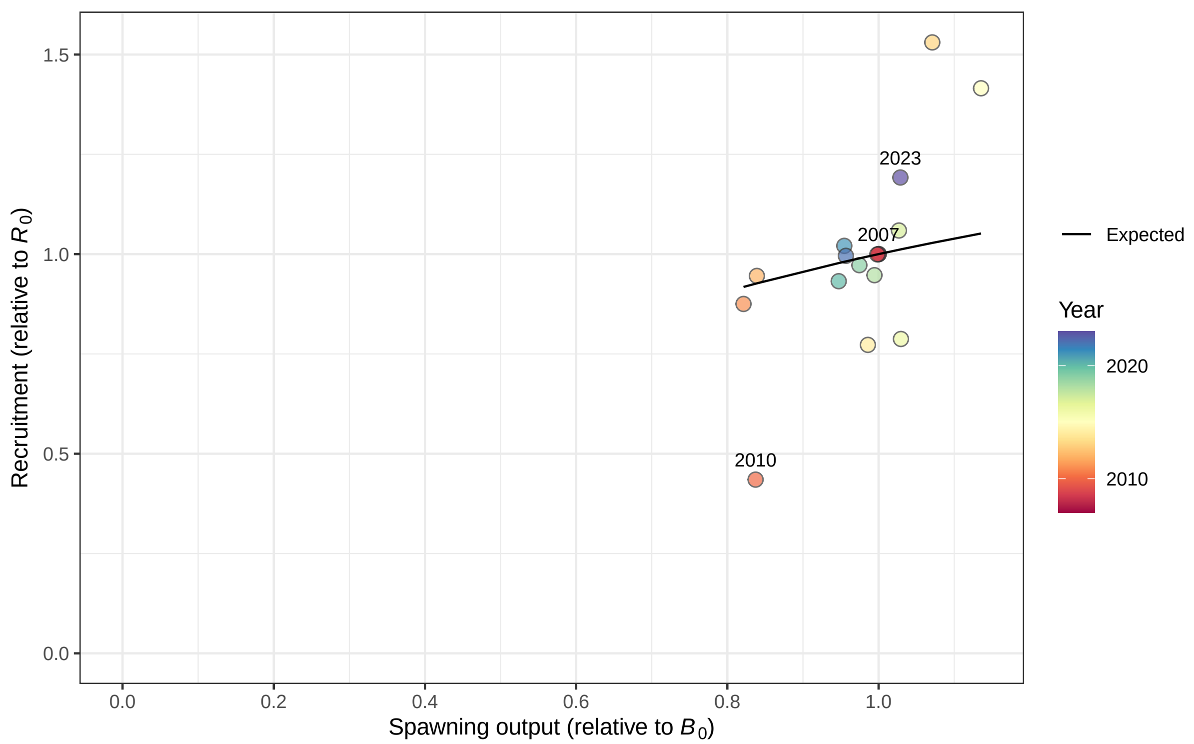


Figure C.11: Stock-recruitment curve estimated via MLE for herrmanni curryfish. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

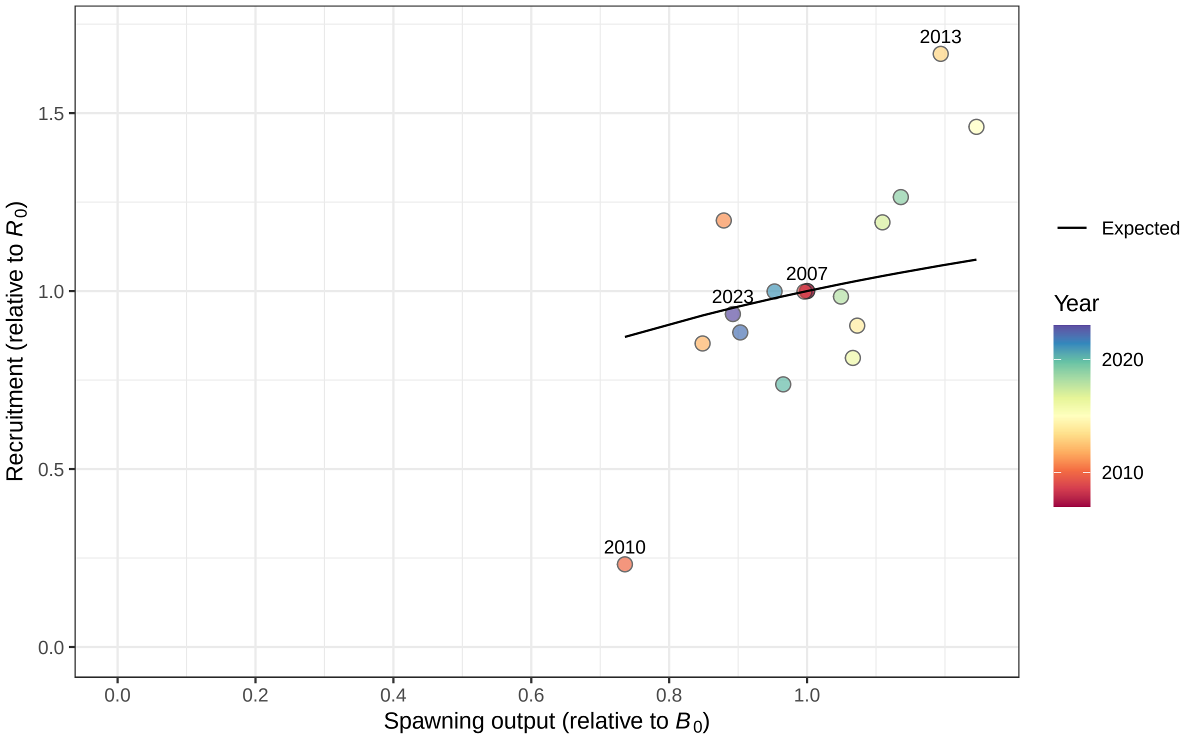


Figure C.12: Stock-recruitment curve estimated via MLE for vastus curryfish. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

C.4 Recruitment deviations

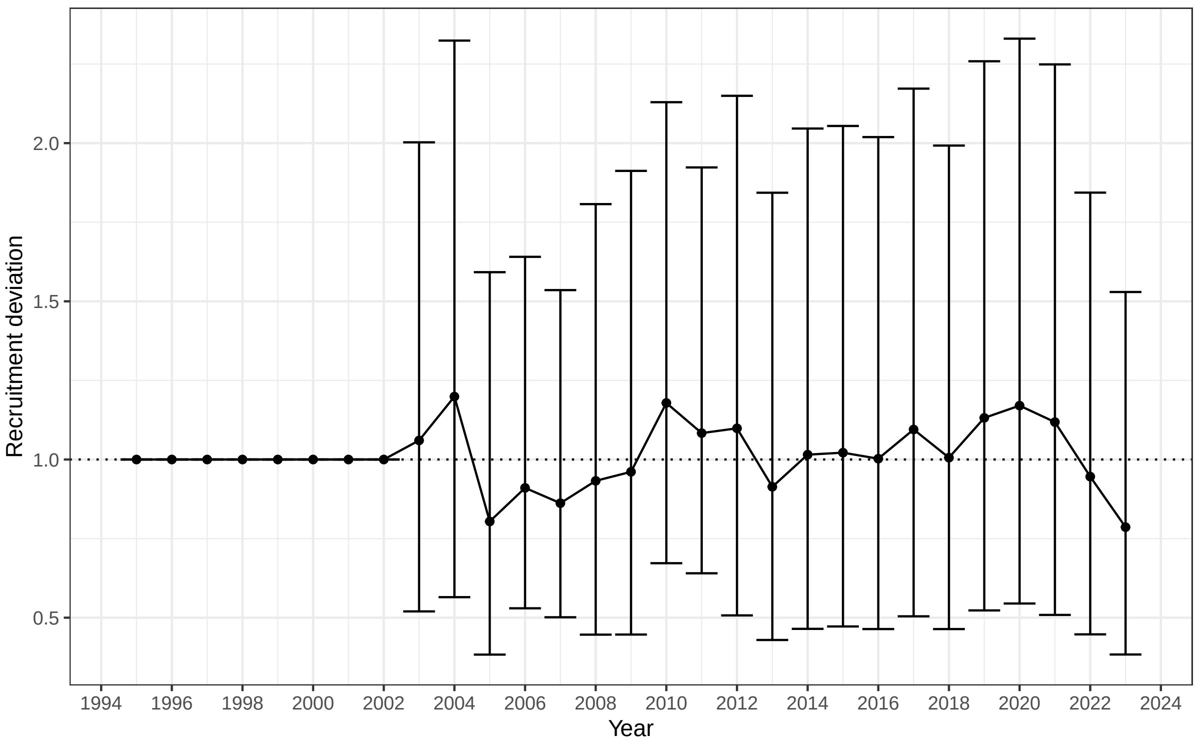


Figure C.13: Recruitment deviations (MCMC posterior medians) for prickly redfish, from 1995 to 2023.

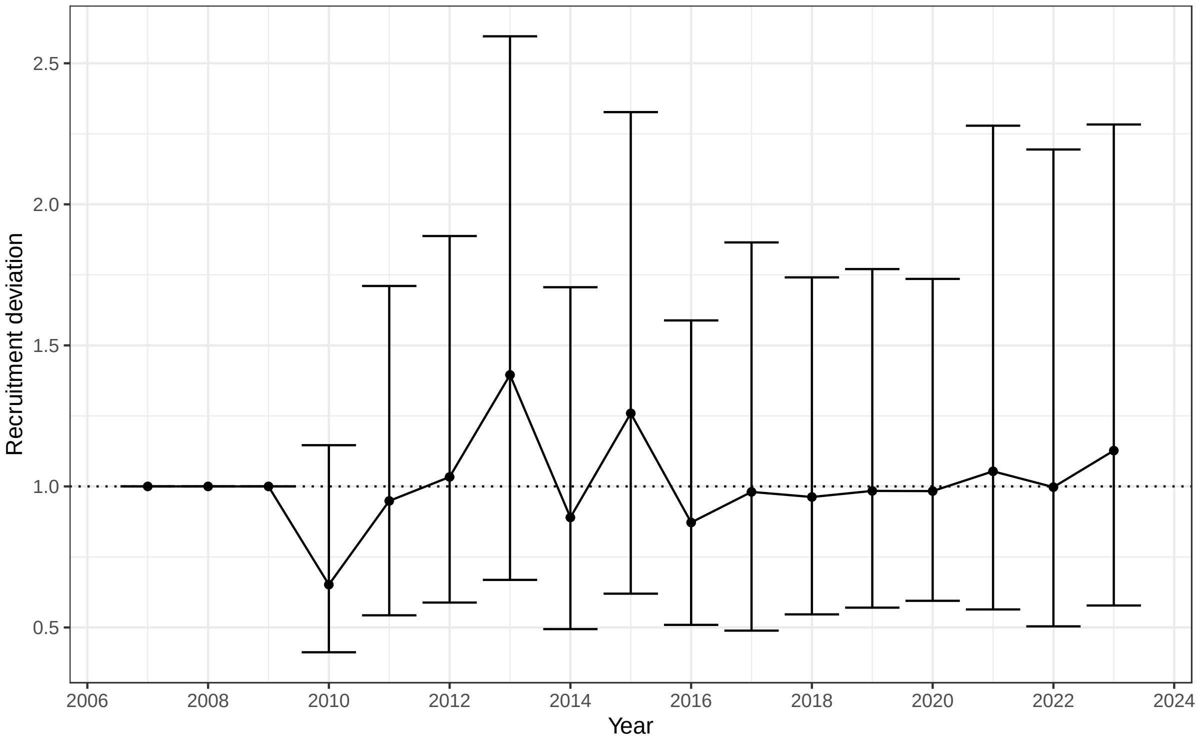


Figure C.14: Recruitment deviations (MCMC posterior medians) for herrmanni curryfish, from 2007 to 2023.

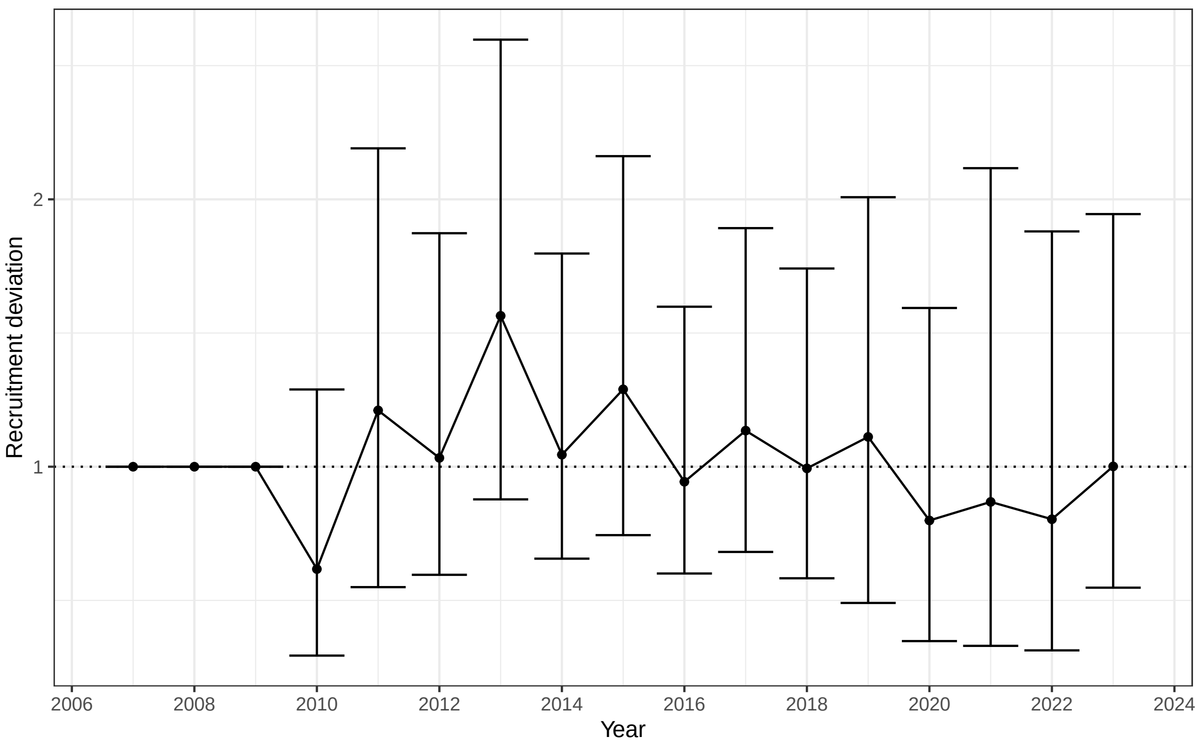


Figure C.15: Recruitment deviations (MCMC posterior medians) for vastus curryfish, from 2007 to 2023.

C.5 Fishing mortality

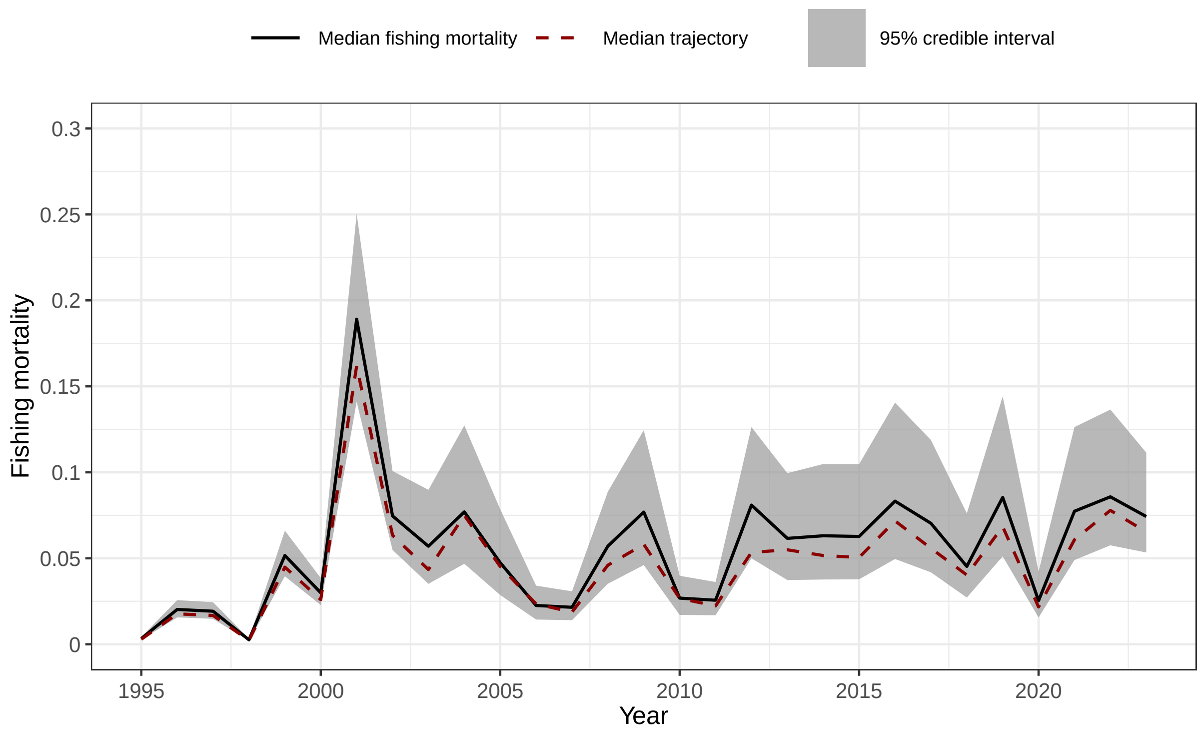


Figure C.16: Predicted legal-sized F from DDUST MCMC and MLE for prickly redfish, from 1995 to 2023.

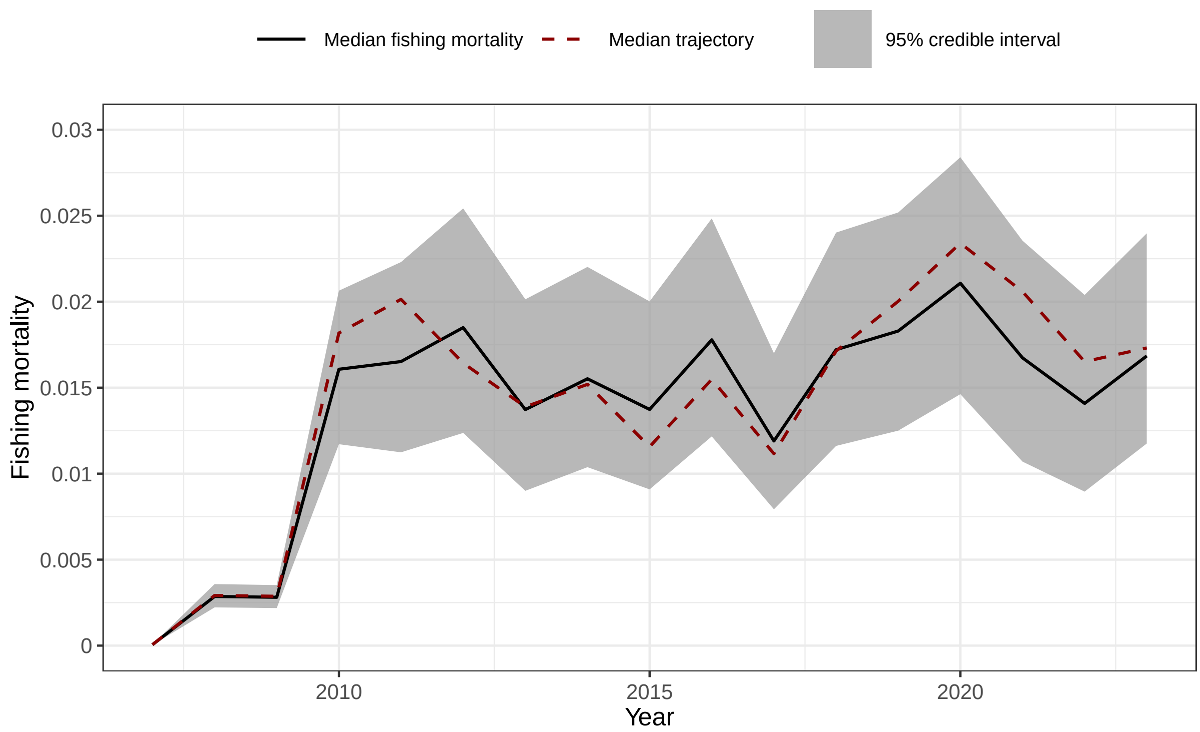


Figure C.17: Predicted legal-sized F from DDUST MCMC and MLE for herrmanni curryfish, from 2007 to 2023.

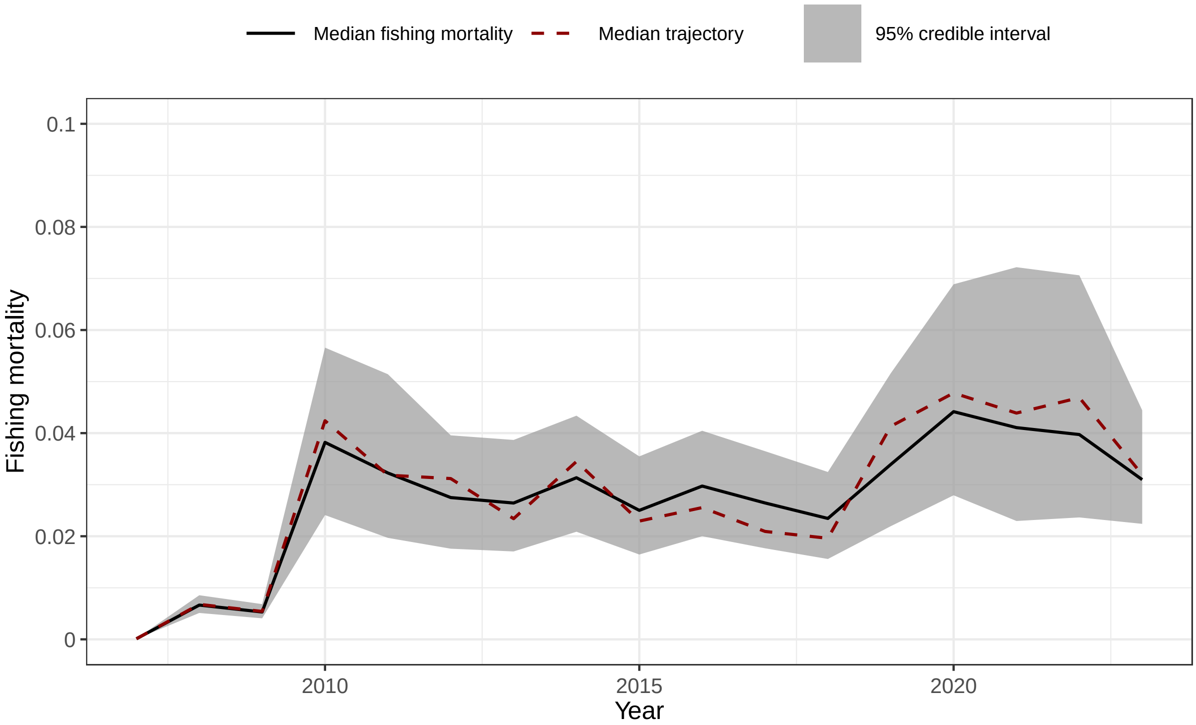


Figure C.18: Predicted legal-sized F from DDUST MCMC and MLE for vastus curryfish, from 2007 to 2023.

Appendix D Stock Synthesis MCMC diagnostics

D.1 Potential scale reduction factor

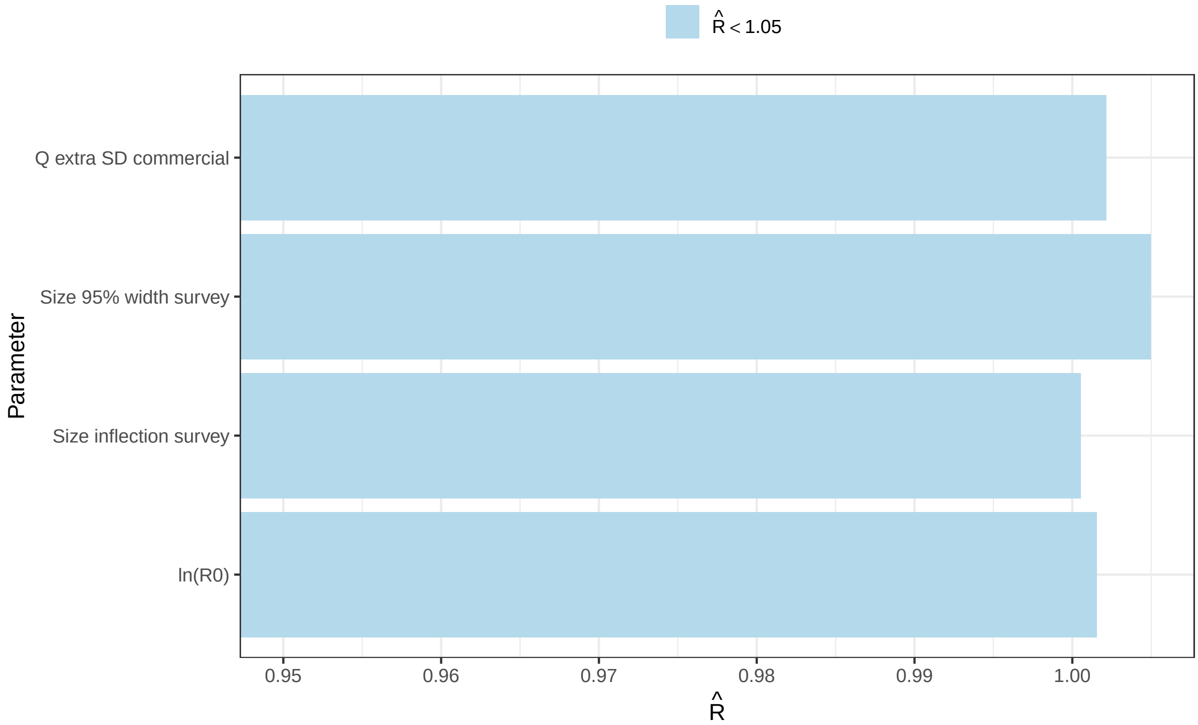


Figure D.1: Potential scale reduction factor plots for prickly redfish base case scenario.

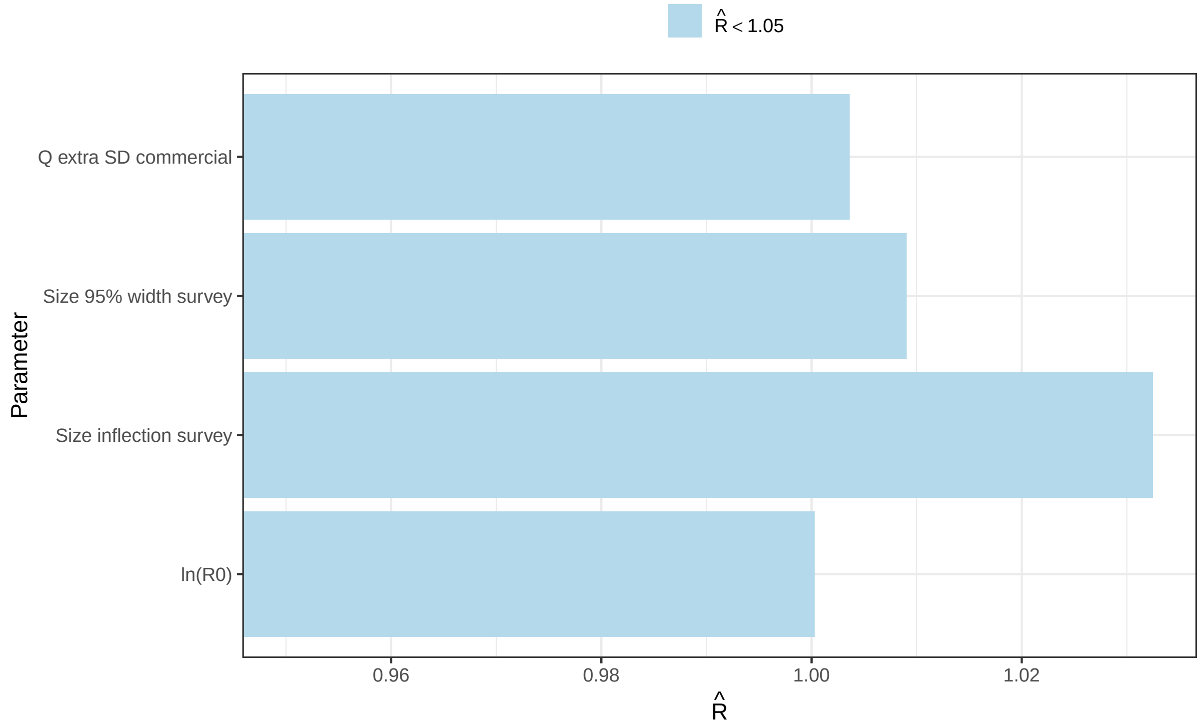


Figure D.2: Potential scale reduction factor plots for herrmanni curryfish base case scenario.

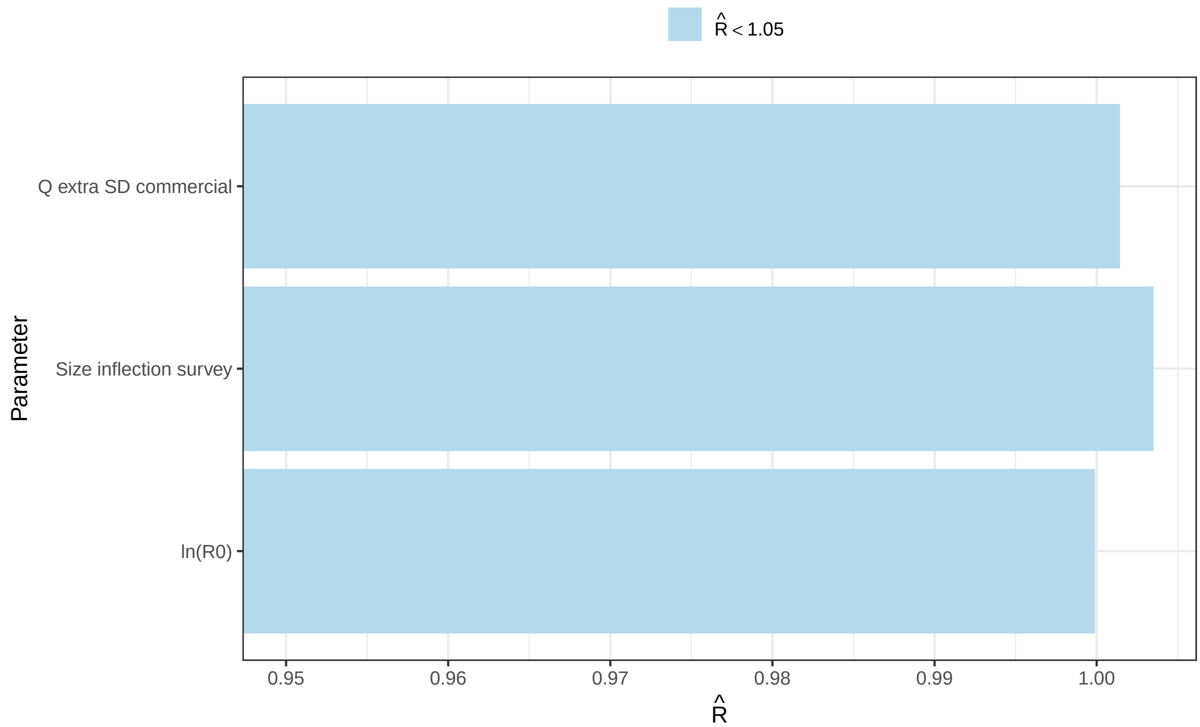


Figure D.3: Potential scale reduction factor plots for vastus curryfish base case scenario.

D.2 Posterior density plots

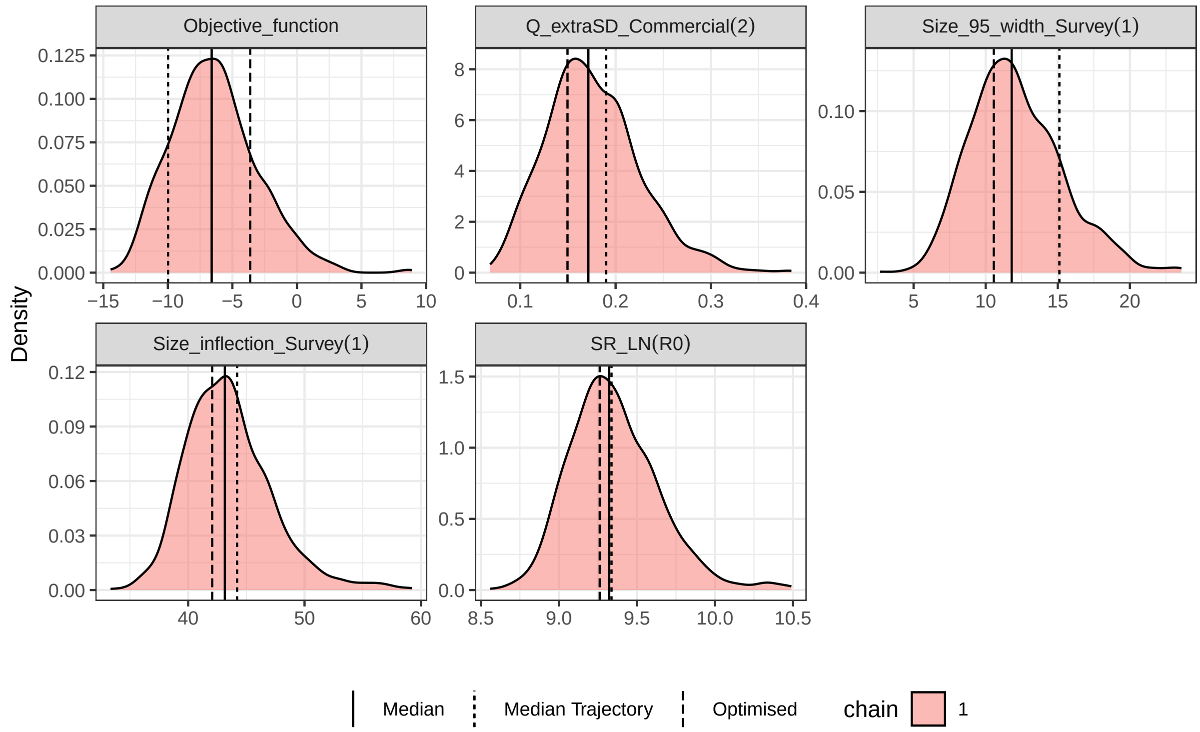


Figure D.4: Posterior density plots for prickly redfish base case Stock Synthesis model.

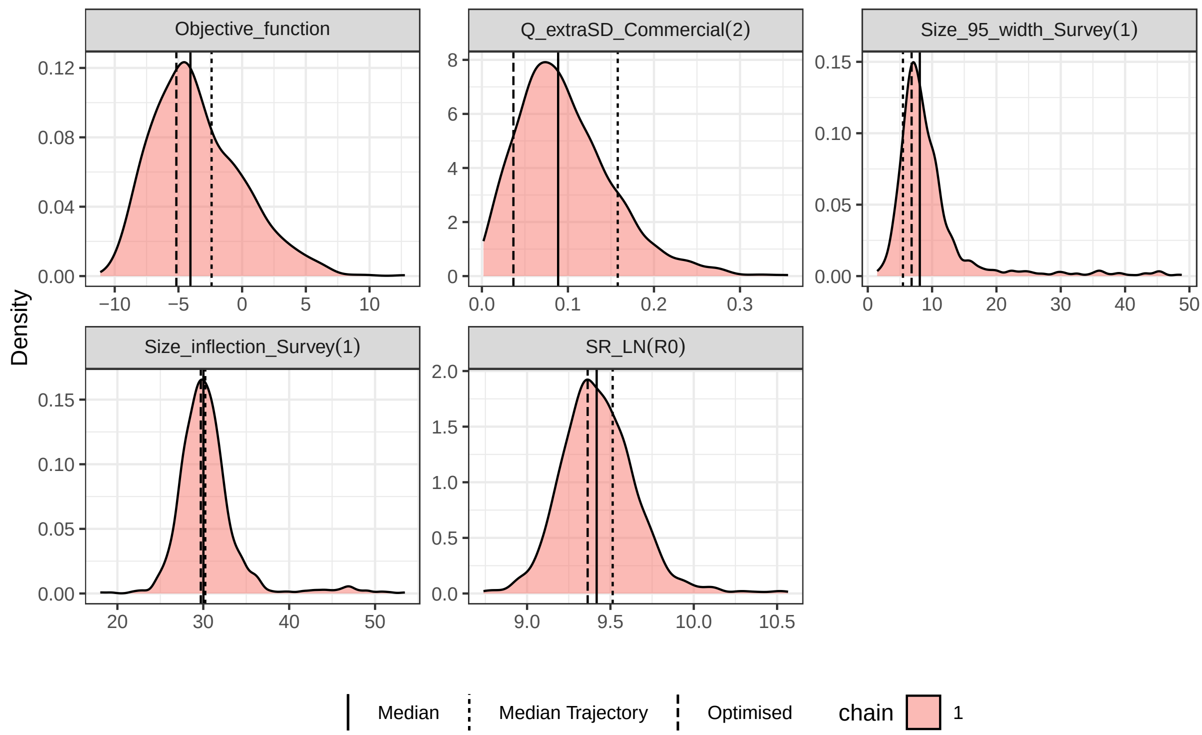


Figure D.5: Posterior density plots for herrmanni curryfish base case Stock Synthesis model.

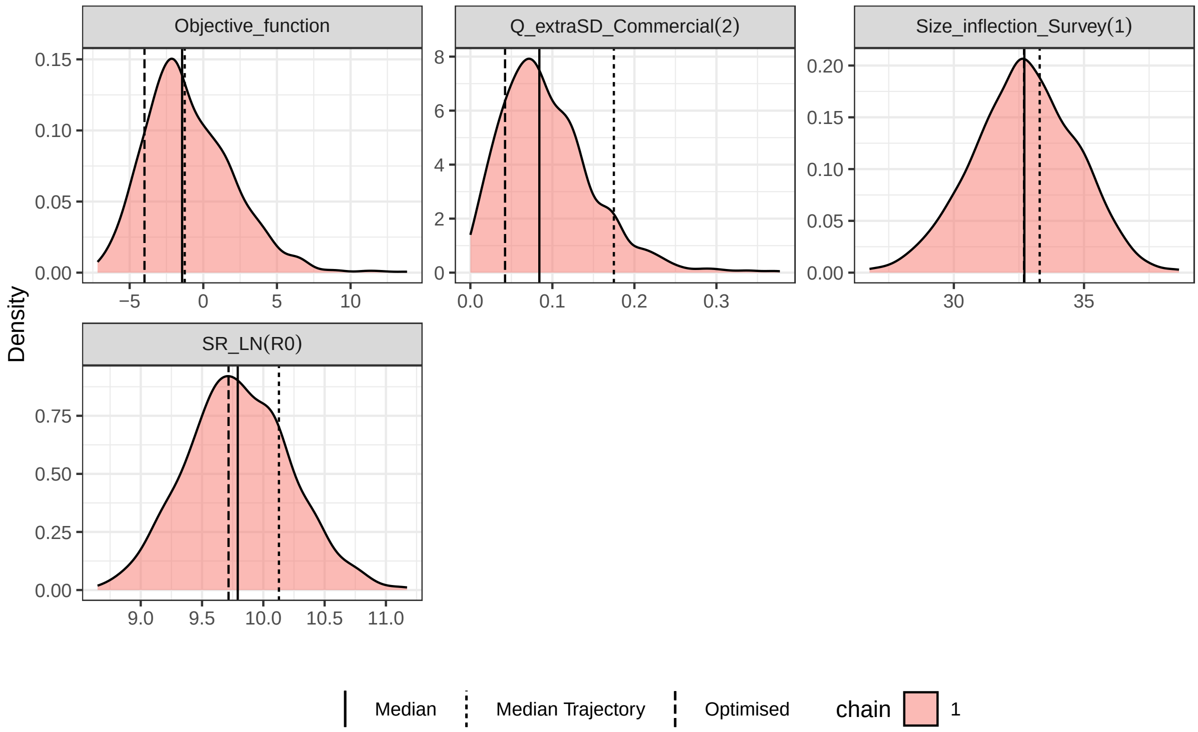


Figure D.6: Posterior density plots for vastus curryfish base case Stock Synthesis model.

D.3 Trace plots

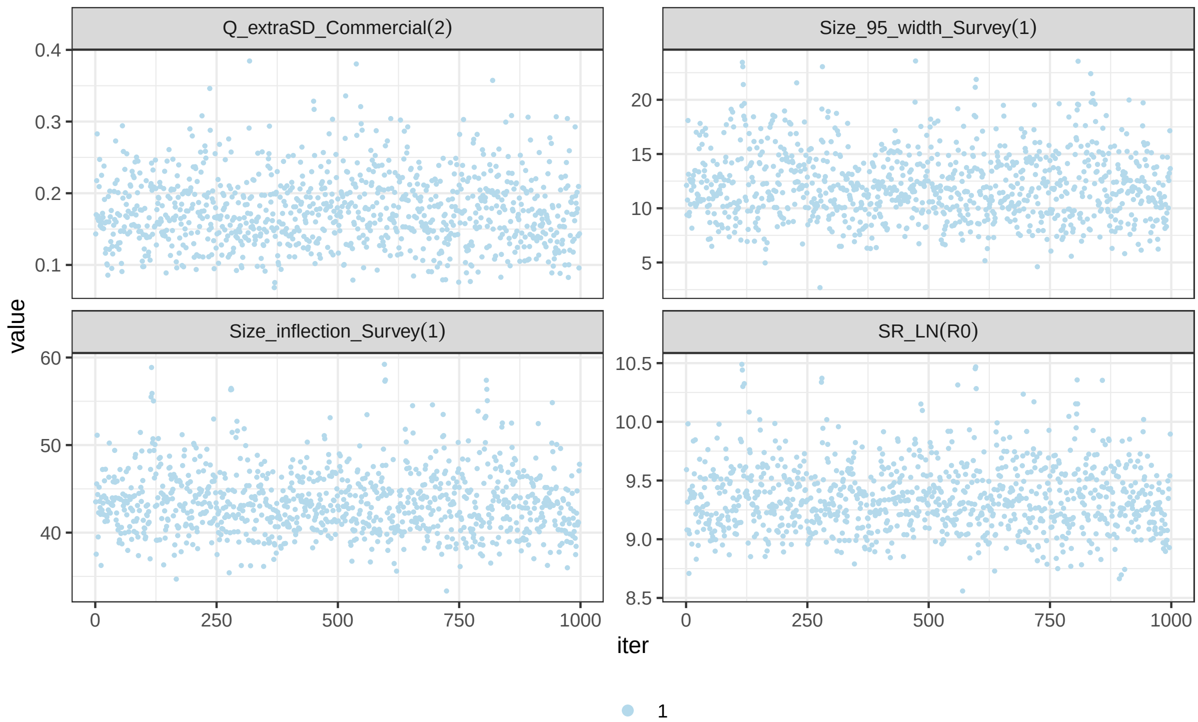


Figure D.7: Trace plots for prickly redfish base case Stock Synthesis model.

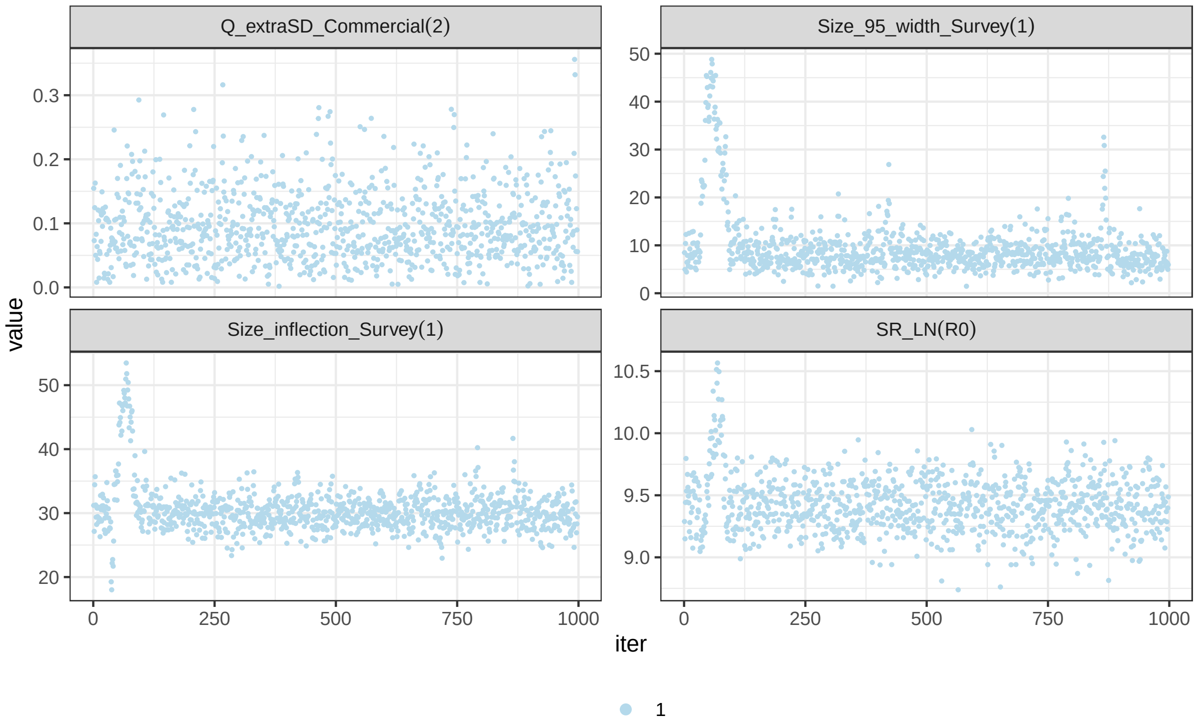


Figure D.8: Trace plots for herrmanni curryfish base case Stock Synthesis model.

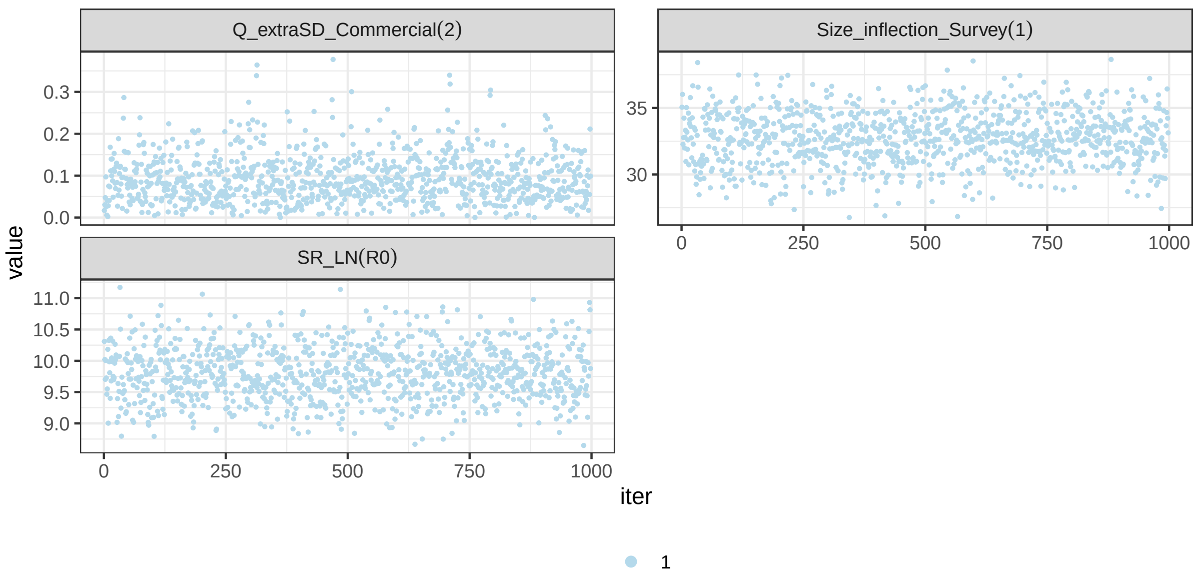


Figure D.9: Trace plots for vastus curryfish base case Stock Synthesis model.

D.4 Correlation plots

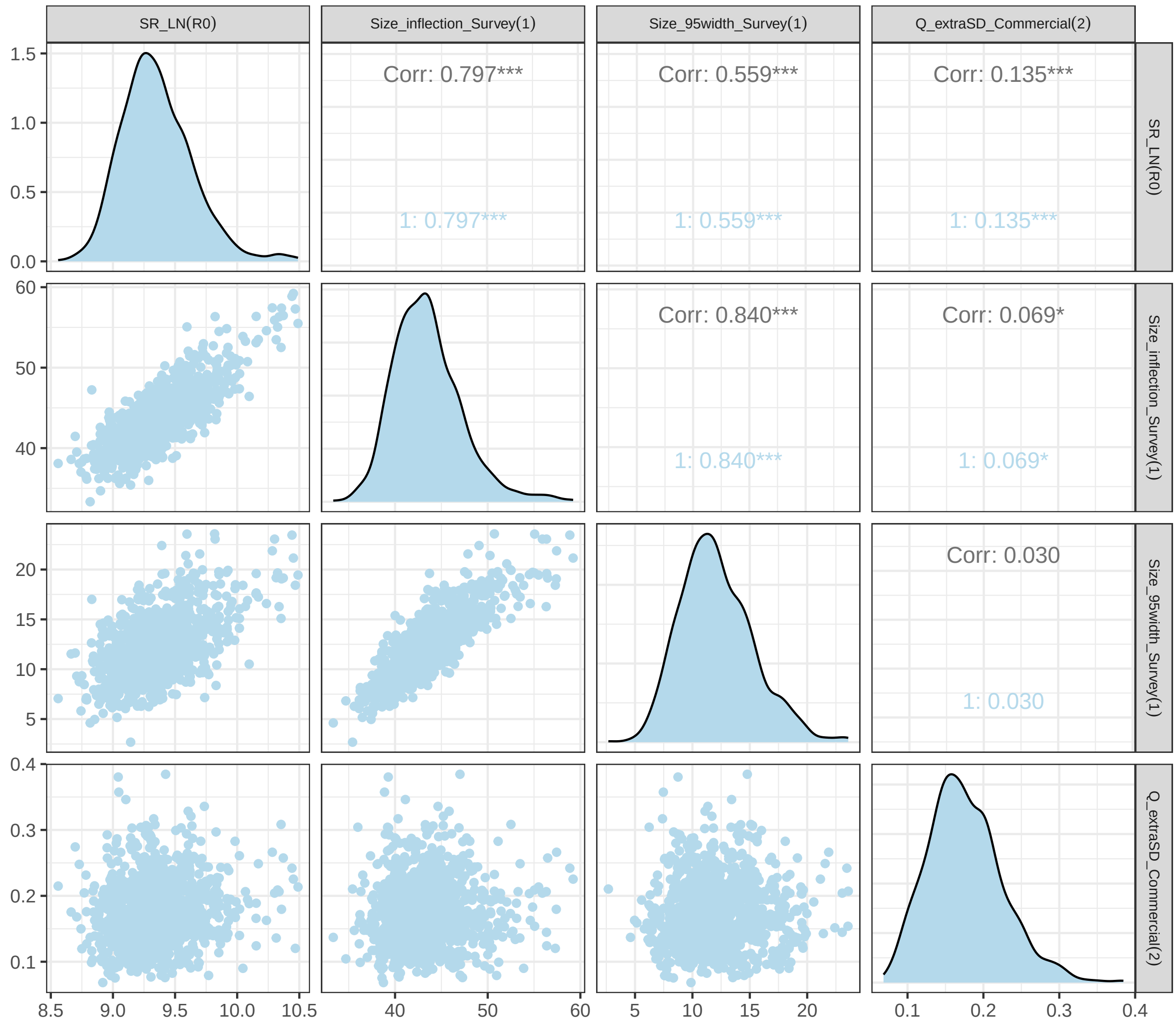


Figure D.10: Parameter correlation plots for prickly redfish base case Stock Synthesis model.

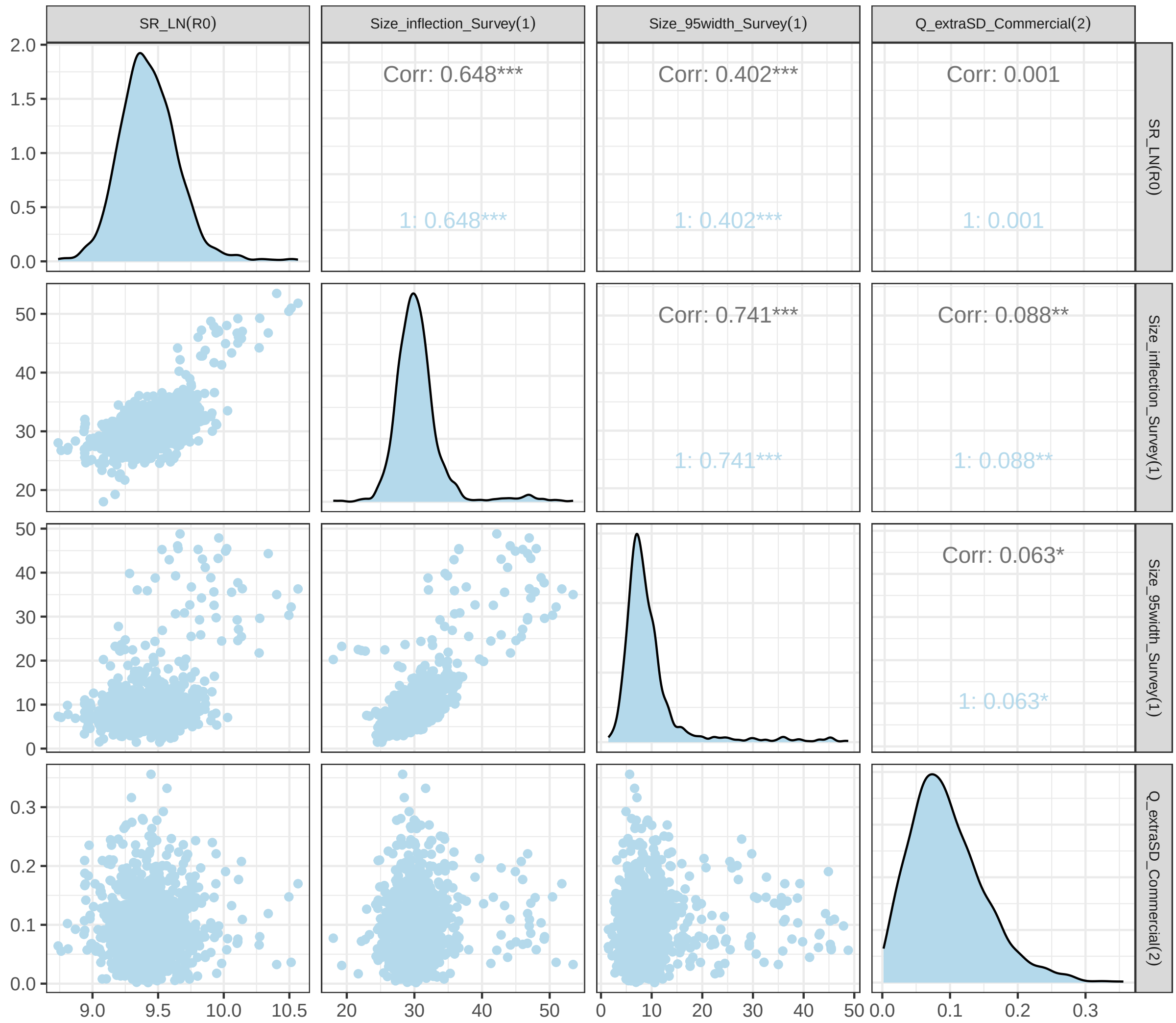


Figure D.11: Parameter correlation plots for herrmanni curryfish base case Stock Synthesis model.

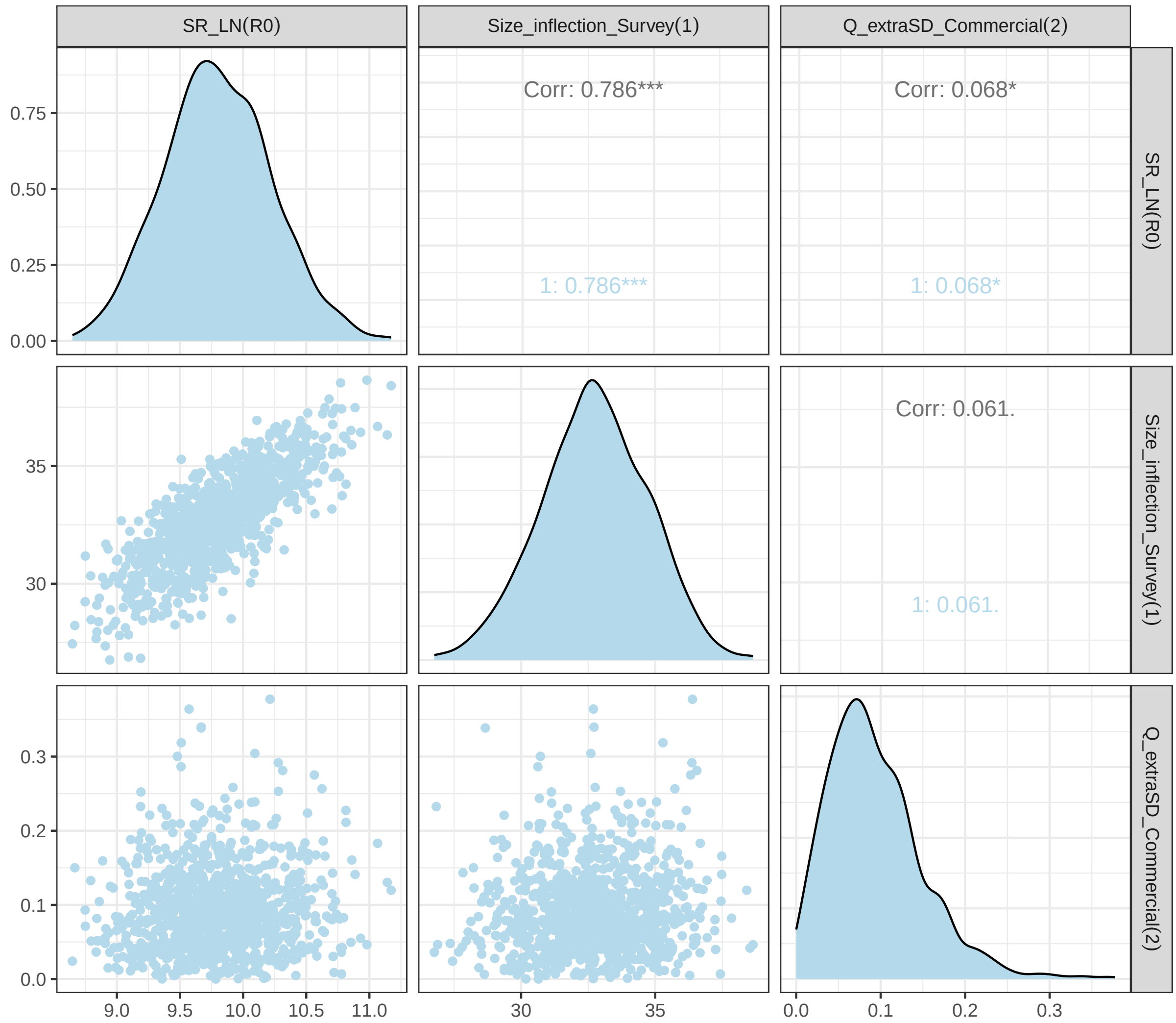


Figure D.12: Parameter correlation plots for vastus curryfish base case Stock Synthesis model.

D.5 Natural mortality likelihood profile plots

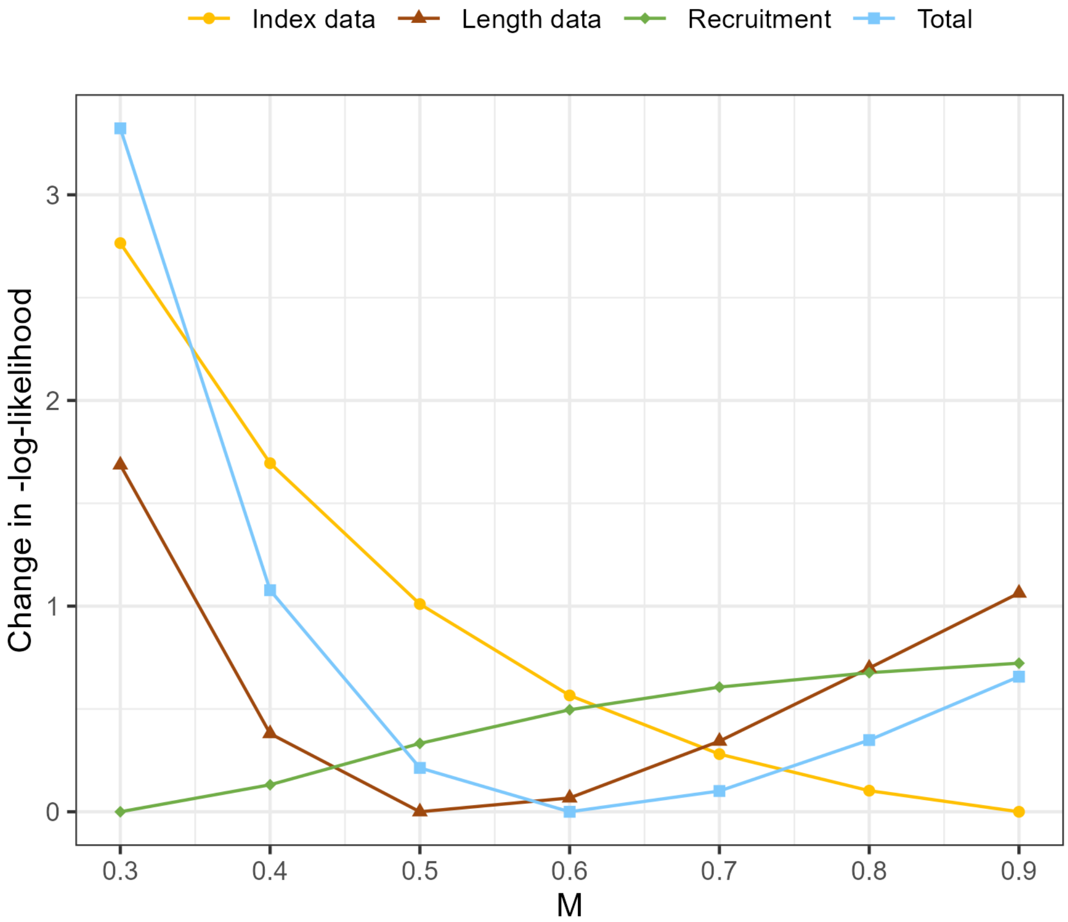


Figure D.13: Natural mortality (M) likelihood profile for the prickly redfish base case Stock Synthesis model.

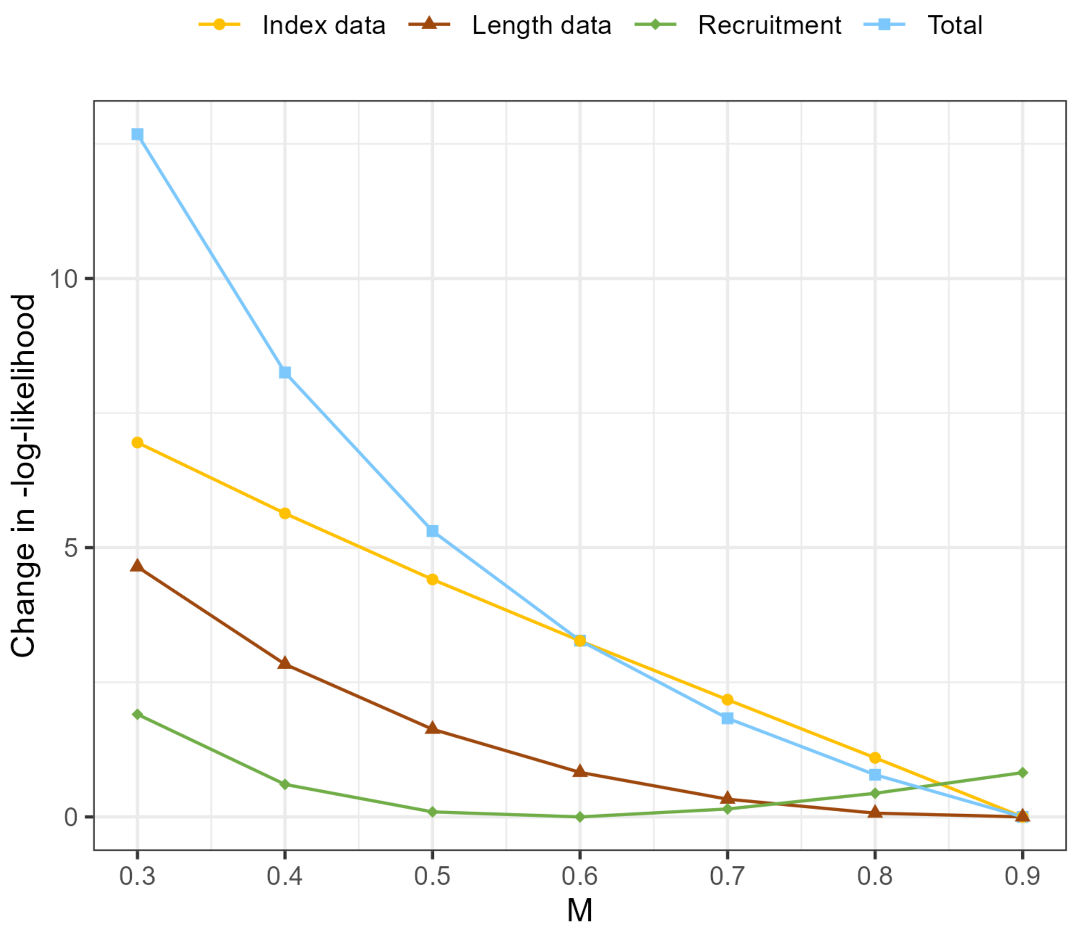


Figure D.14: Natural mortality (M) likelihood profile for the herrmanni curryfish base case Stock Synthesis model.

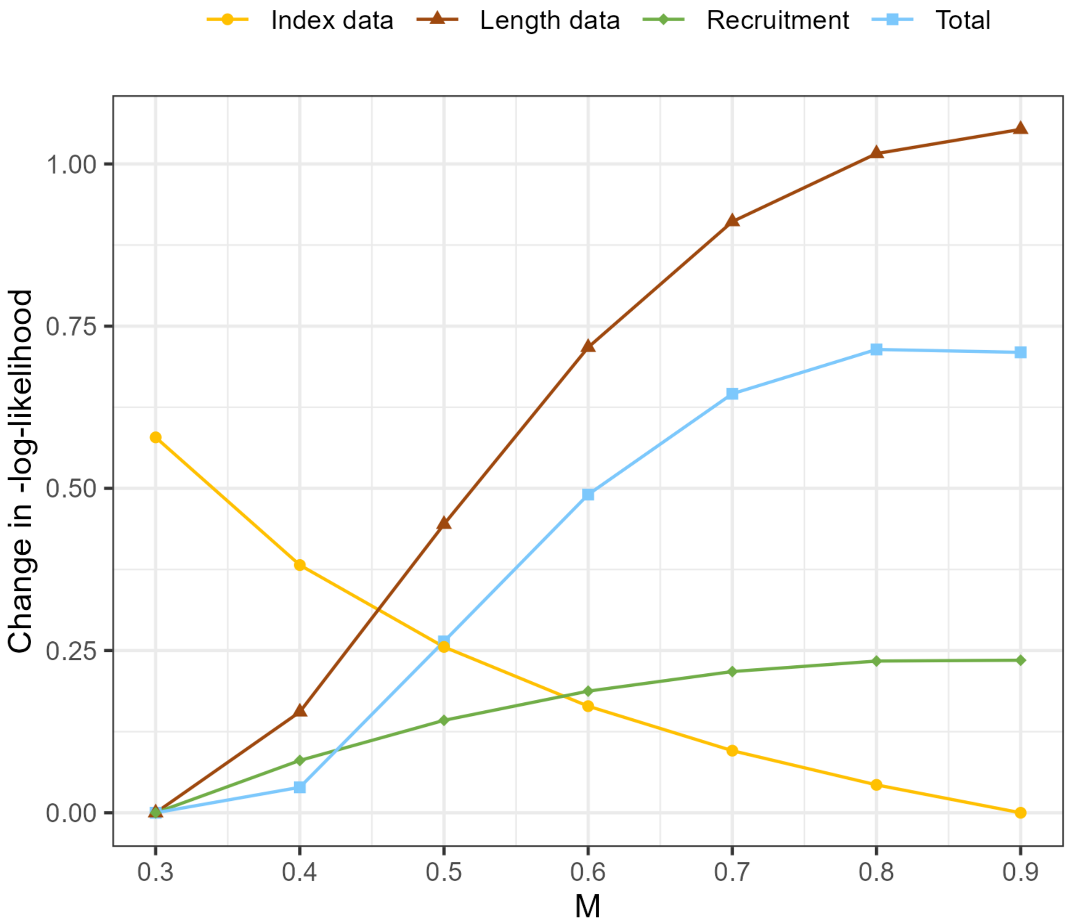


Figure D.15: Natural mortality (M) likelihood profile for the vatus curryfish base case Stock Synthesis model.

Appendix E DDUST MCMC diagnostics

E.1 Posterior density plots

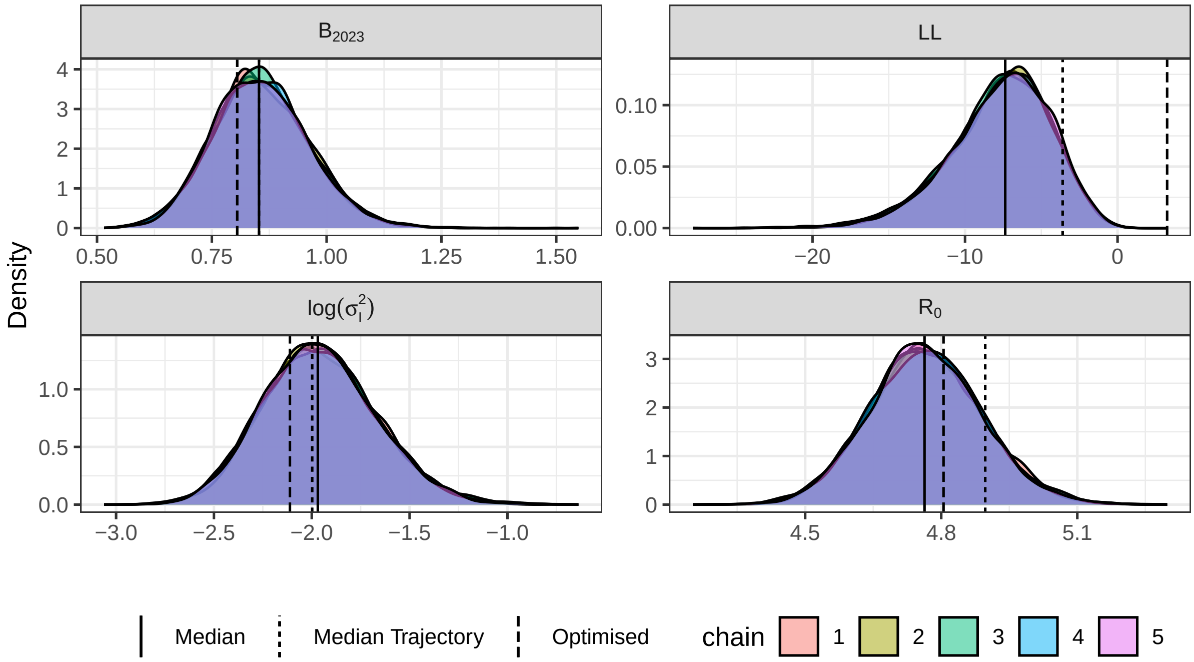


Figure E.1: Posterior density plots for prickly redfish base case DDUST model.

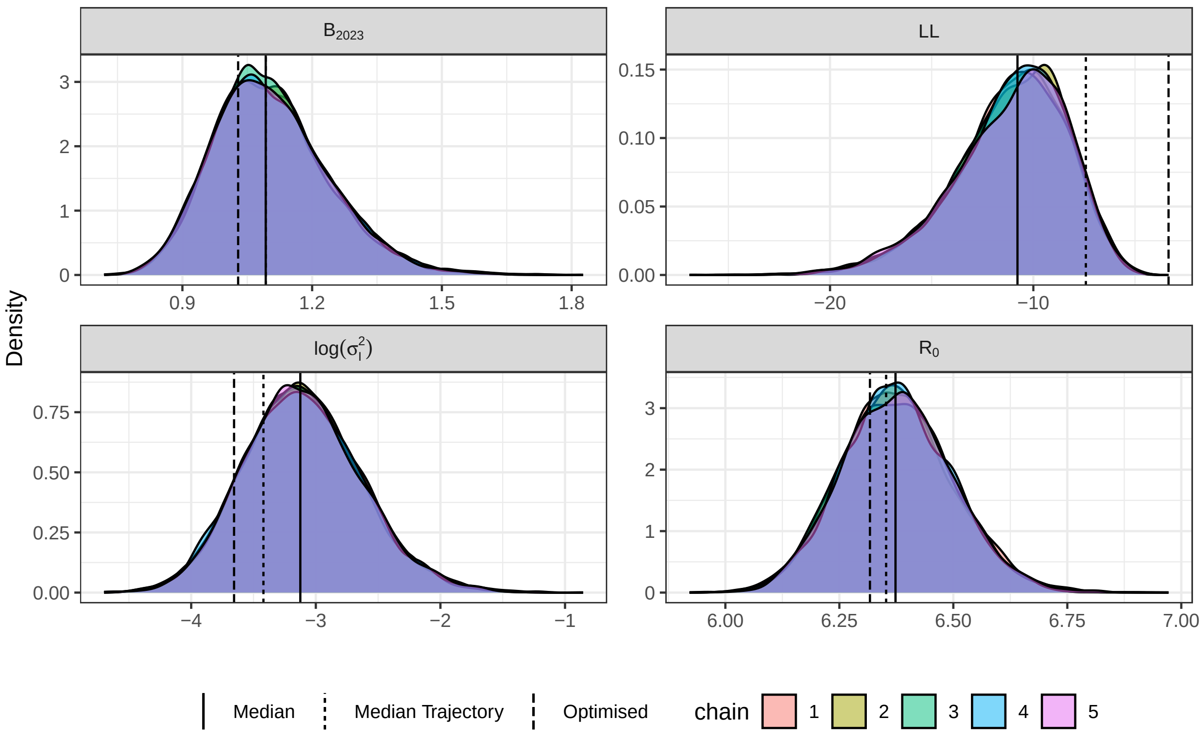


Figure E.2: Posterior density plots for herrmanni curryfish base case DDUST model.

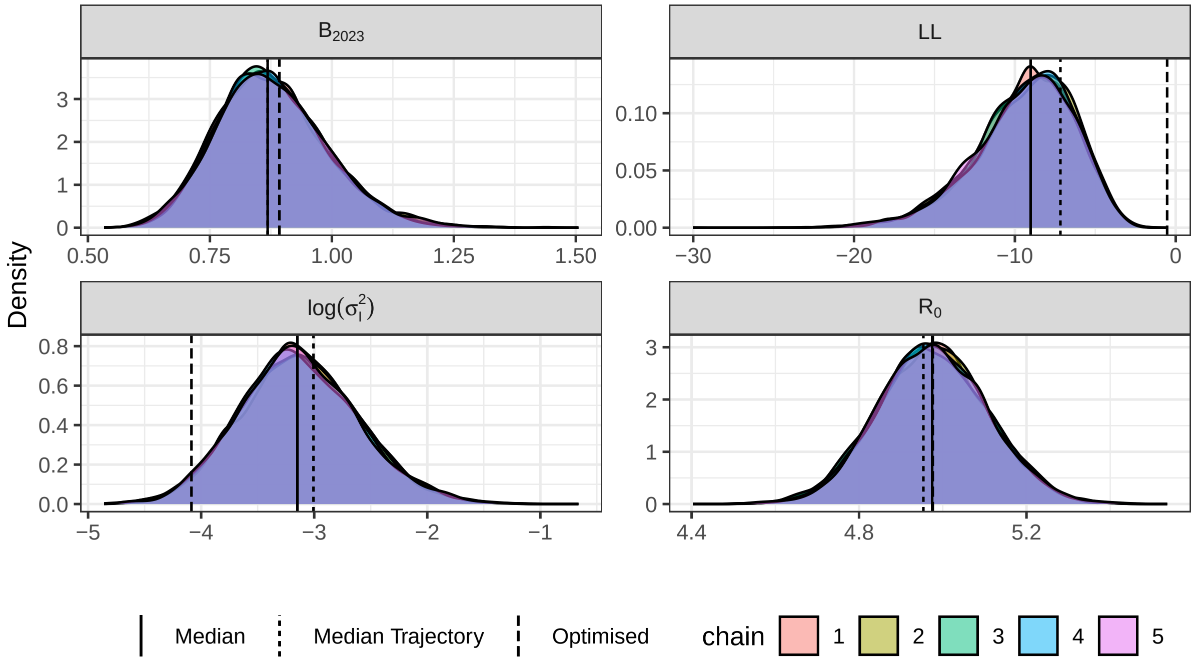


Figure E.3: Posterior density plots for vastus curryfish base case DDUST model.

E.2 Trace plots

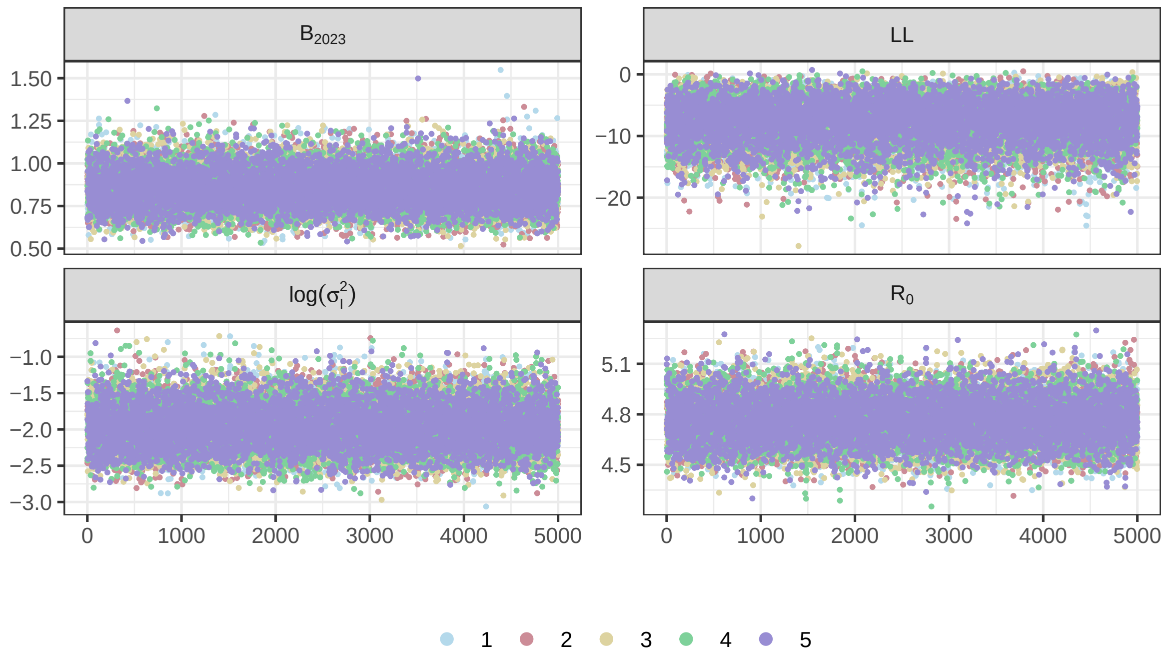


Figure E.4: Trace plots for prickly redfish base case DDUST model.

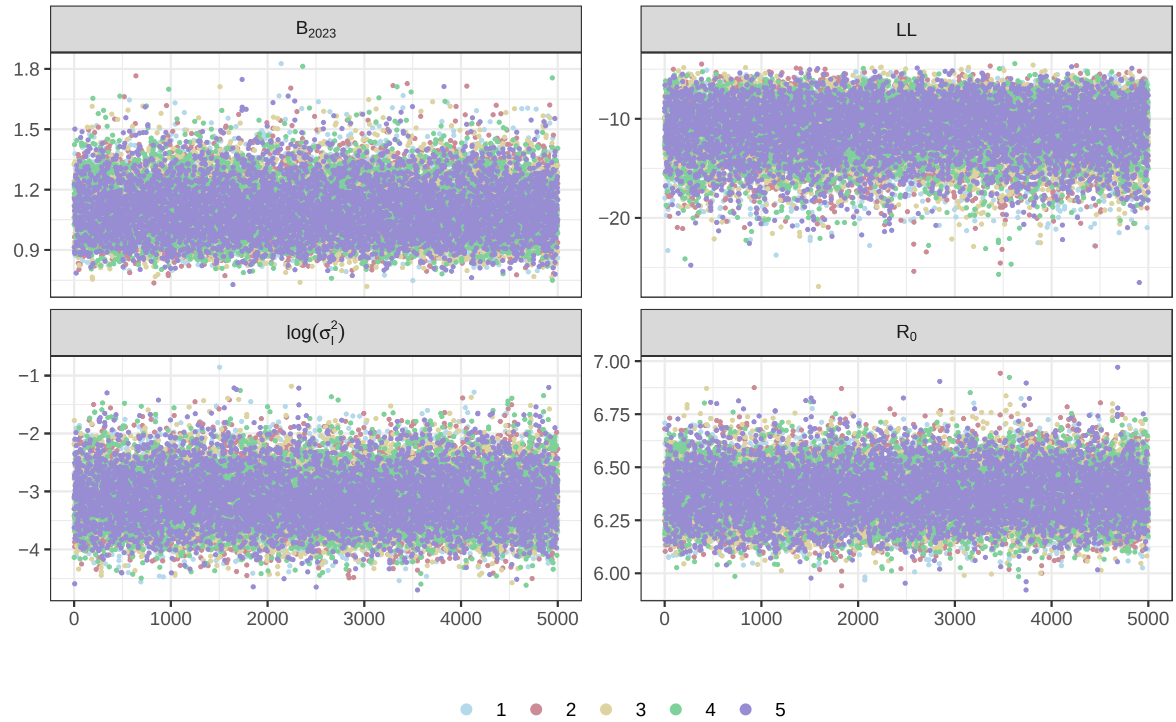


Figure E.5: Trace plots for herrmanni curryfish base case DDUST model.

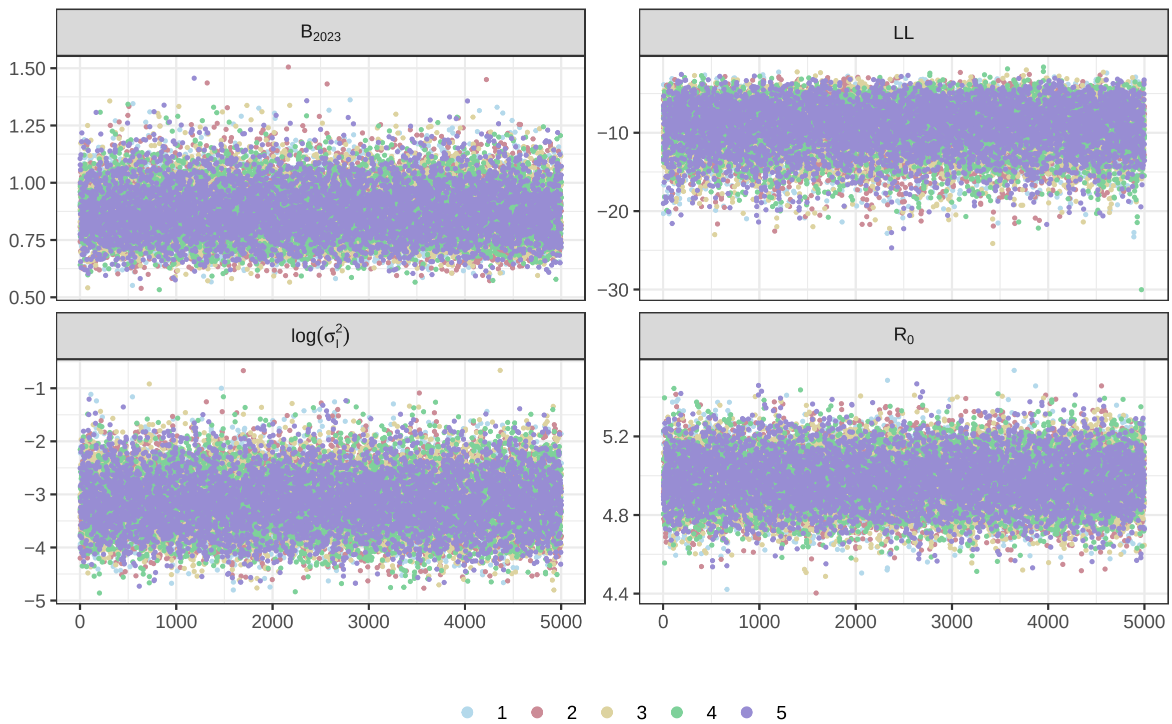


Figure E.6: Trace plots for vastus curryfish base case DDUST model.

E.3 Correlation plots

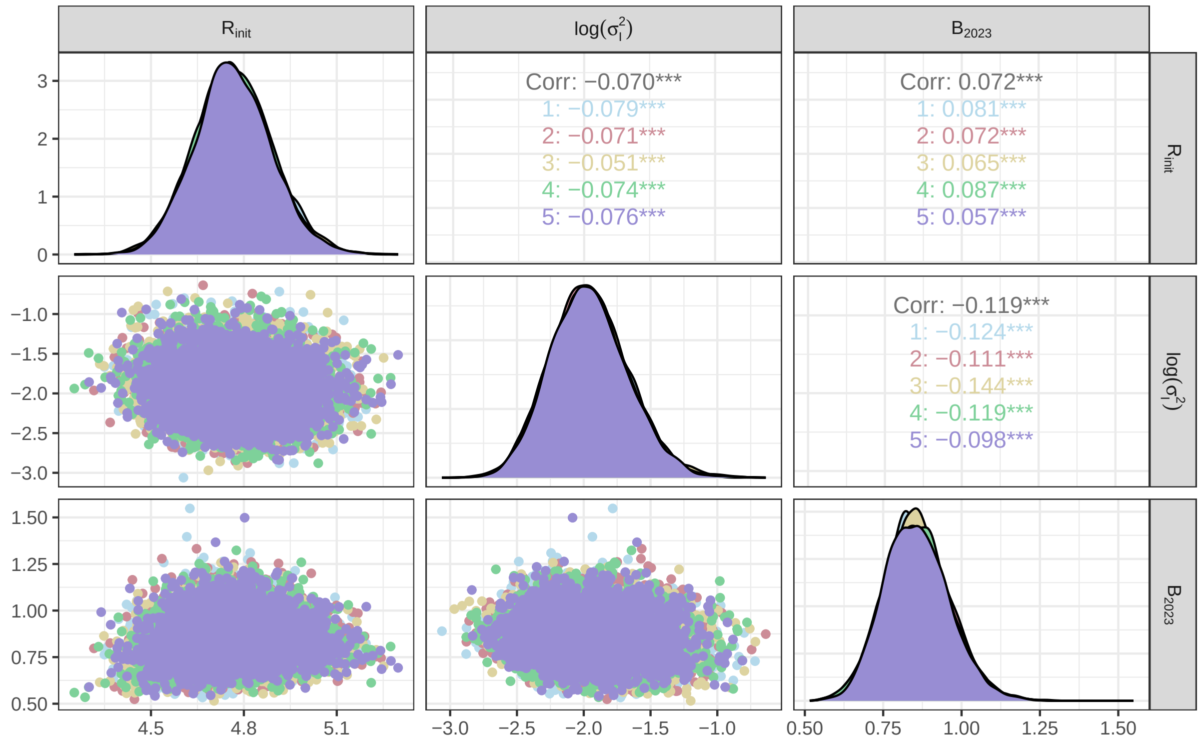


Figure E.7: Parameter correlation plots for prickly redfish base case DDUST model.

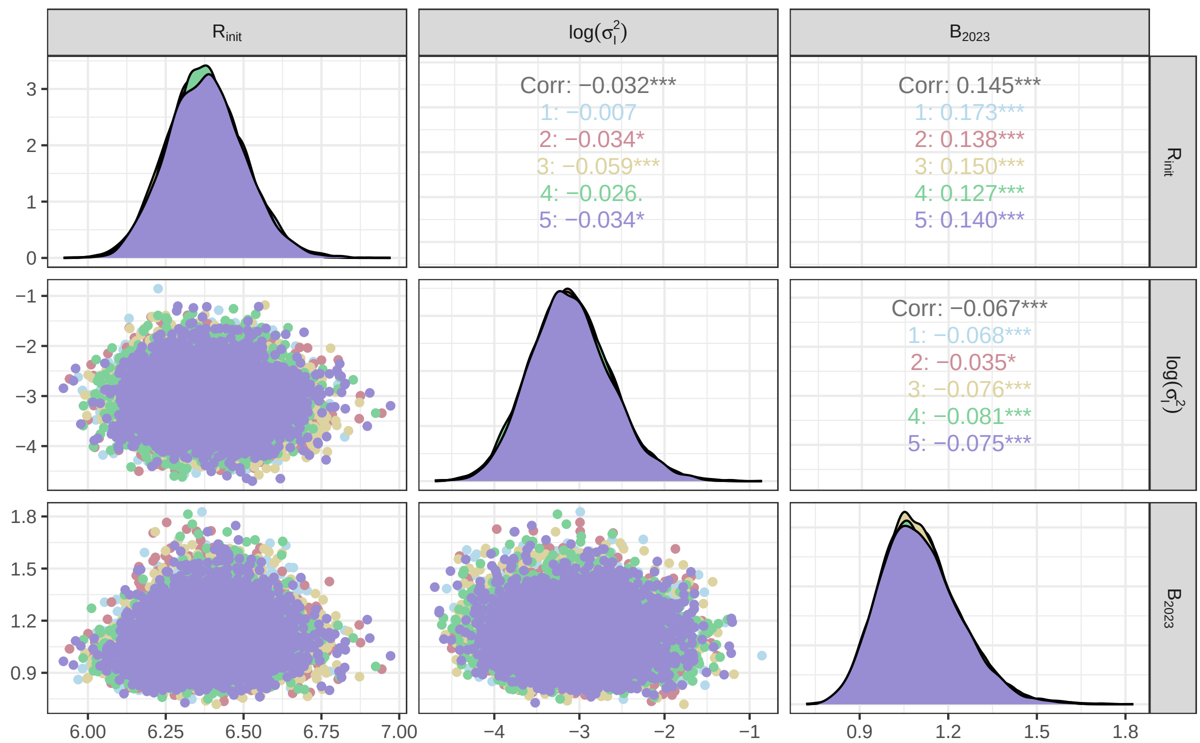


Figure E.8: Parameter correlation plots for herrmanni curryfish base case DDUST model.

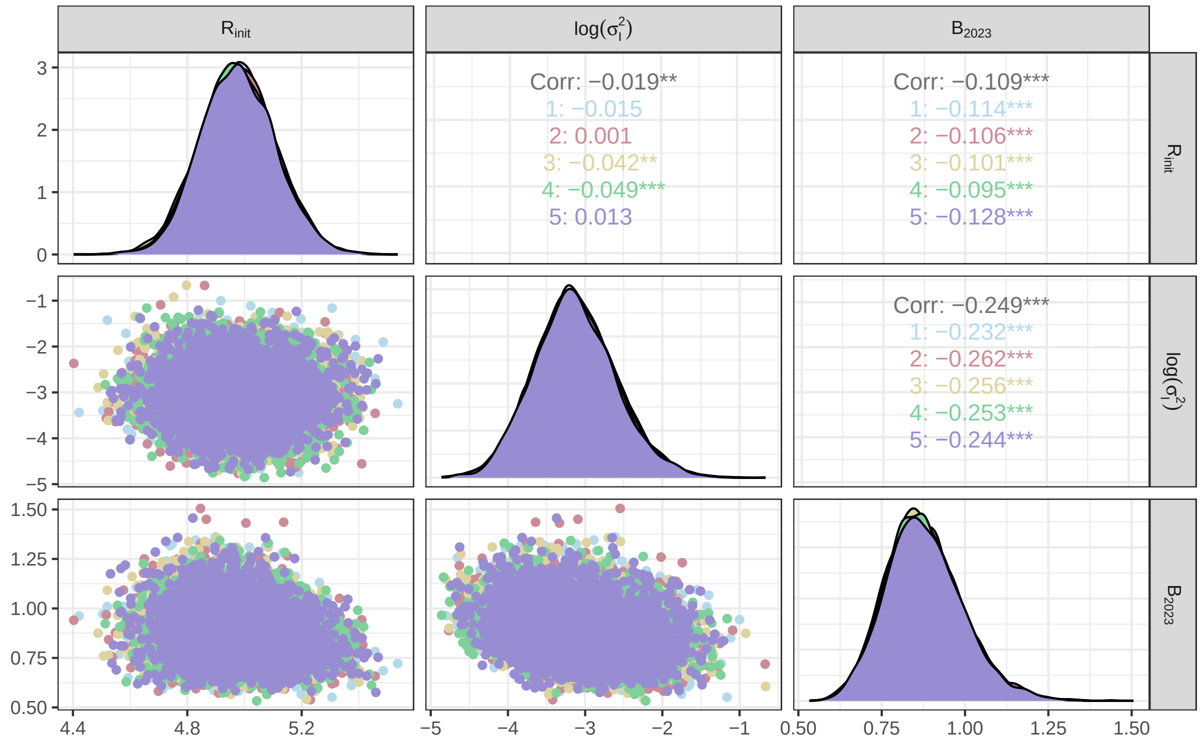


Figure E.9: Parameter correlation plots for vastus curryfish base case DDUST model.

E.4 Natural mortality likelihood profile plots

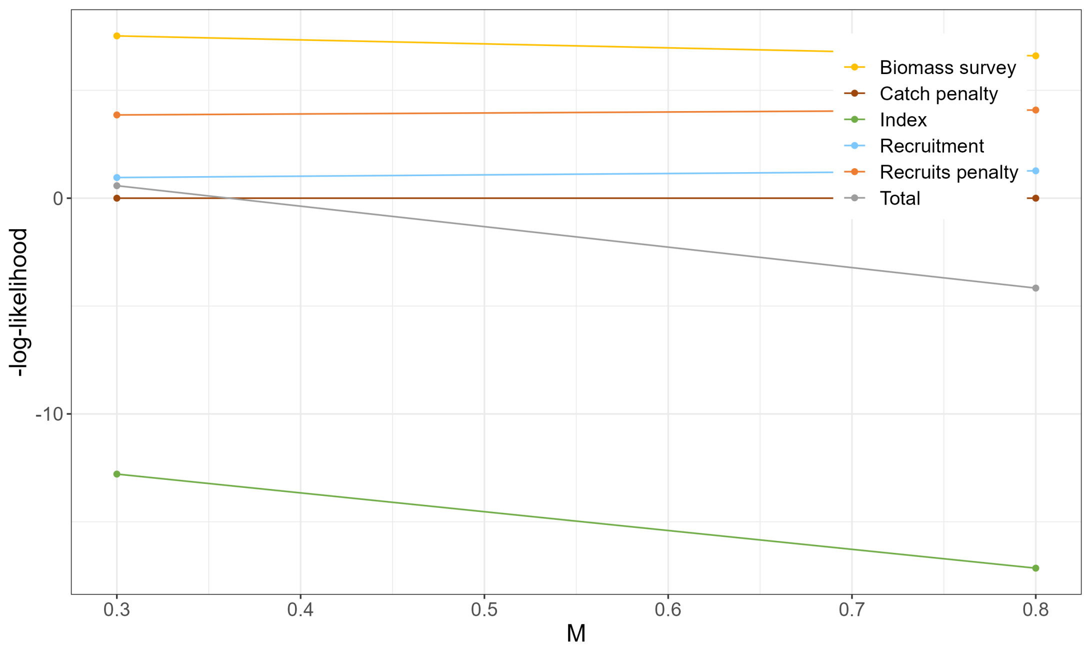


Figure E.10: Natural mortality (M) likelihood profile for the prickly red fish stock base case DDUST model.

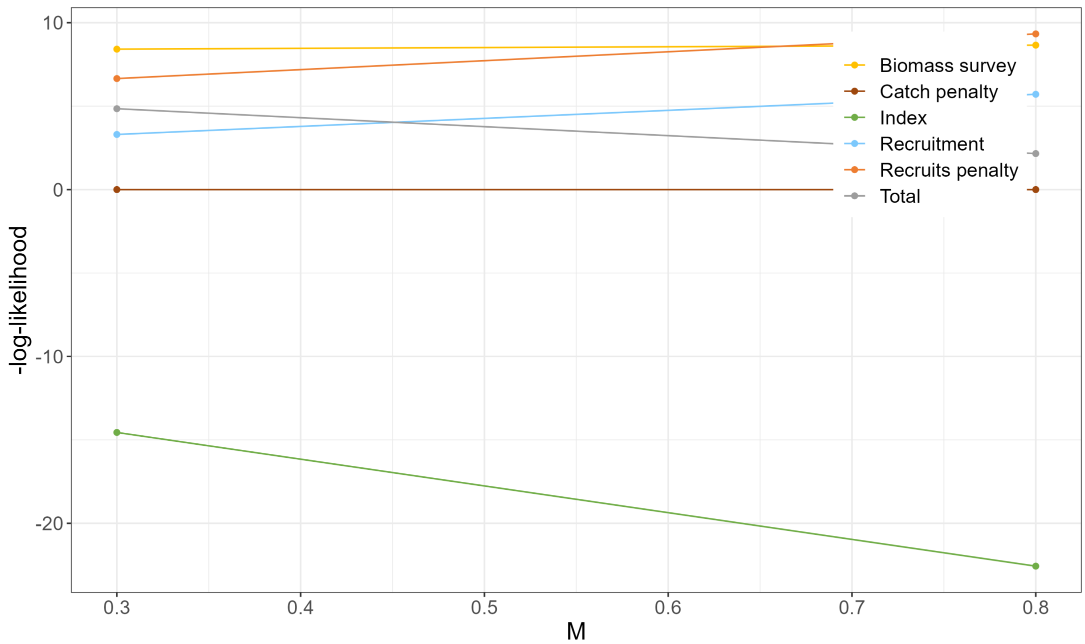


Figure E.11: Natural mortality (M) likelihood profile for the hermanni curryfish stock base case DDUST model.

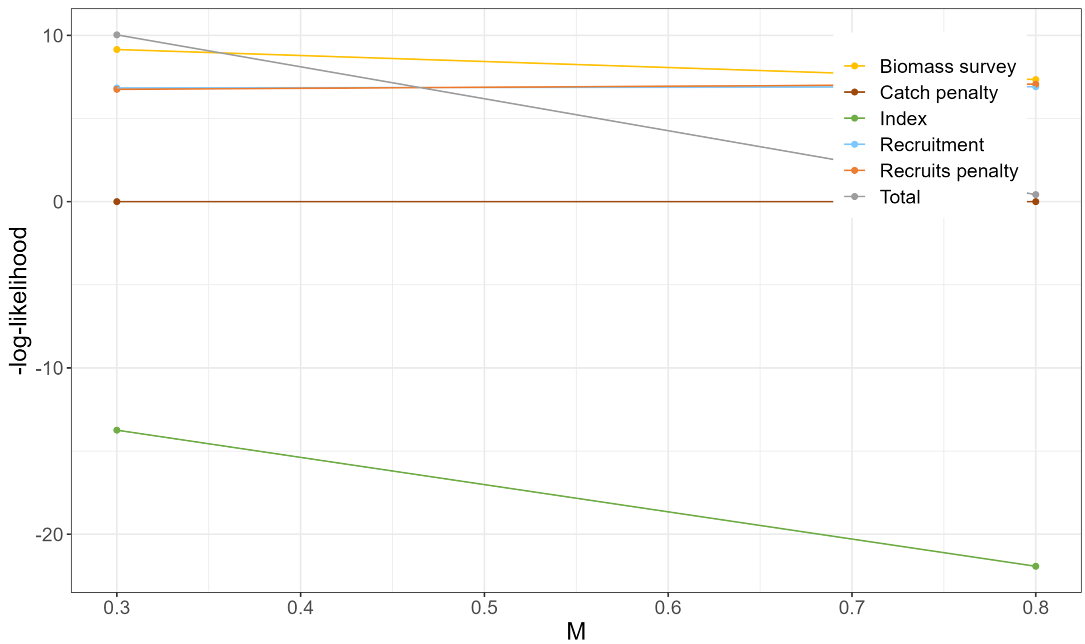


Figure E.12: Natural mortality (M) likelihood profile for the vastus curryfish stock base case DDUST model.

Appendix F Stock Synthesis scenario outputs

Table F.1: Scenarios tested to determine sensitivity to parameters, assumptions and model inputs for Stock Synthesis

Scenario	Species	Description
1	All	Base case
2	All	Low steepness (h)
3	All	High steepness (h)
4	All	Low recruitment variability (σ_R)
5	All	High recruitment variability (σ_R)
6	All	Low natural mortality (M)
7	All	High natural mortality (M)
8	All	Extra catch rate variance
9	All	No survey scaling
10	All	Low survey scaling
11	All	High survey scaling
12	All	Older plus group
13	All	Shrinkage adjustment
14	All	Ricker spawner-recruitment
15	H. curryfish and v. curryfish	Reported logbook catch
16	H. curryfish and v. curryfish	Slower growth
17	H. curryfish and v. curryfish	Faster growth
18	V. curryfish	Earlier maturity
19	V. curryfish	Later maturity
20	P. redfish	Depletion of 60% in 1940

F.1 Sensitivity

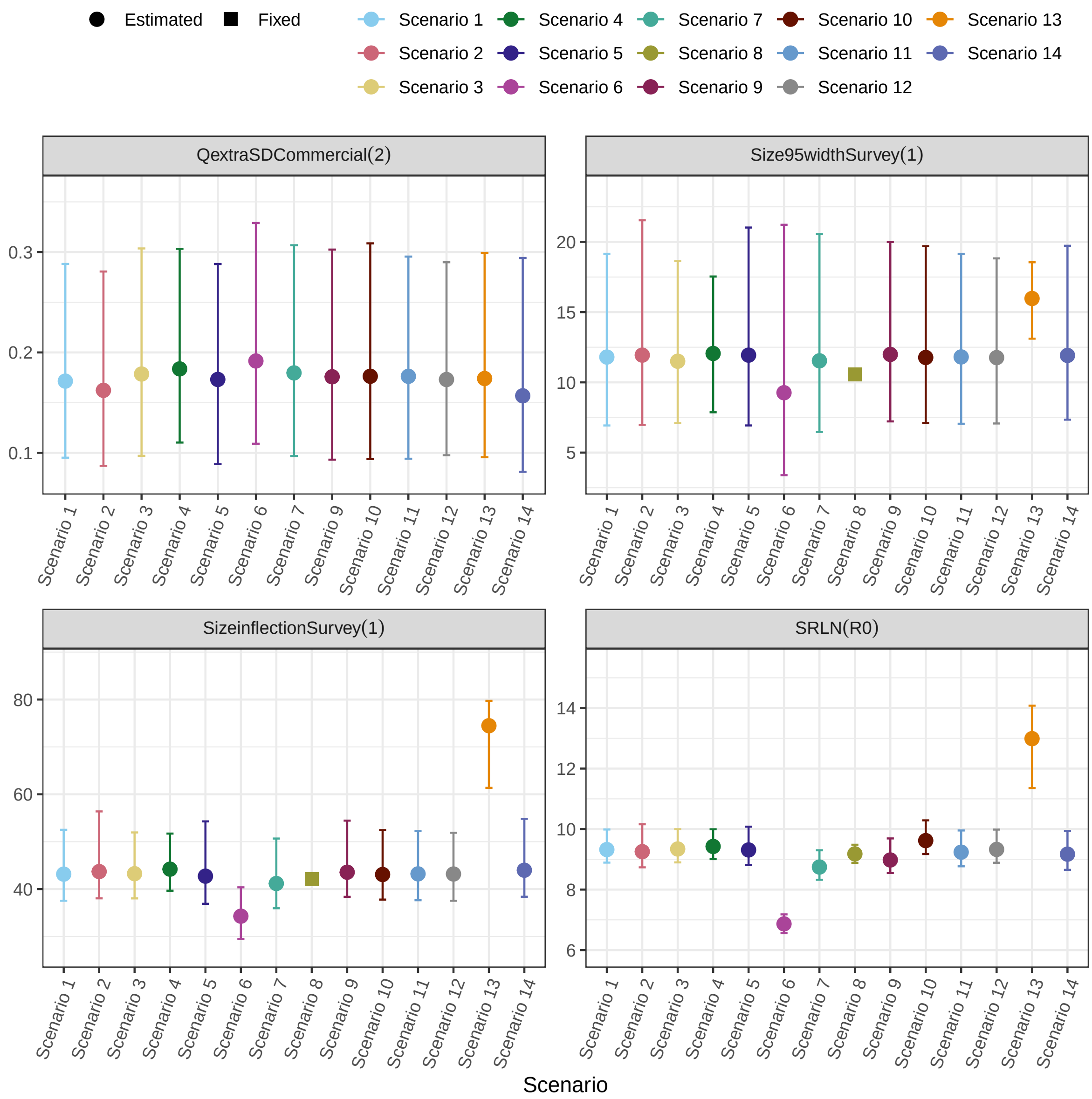


Figure F.1: Stock Synthesis sensitivity plots of estimated parameters for fourteen (out of fifteen) scenarios for prickly redfish.

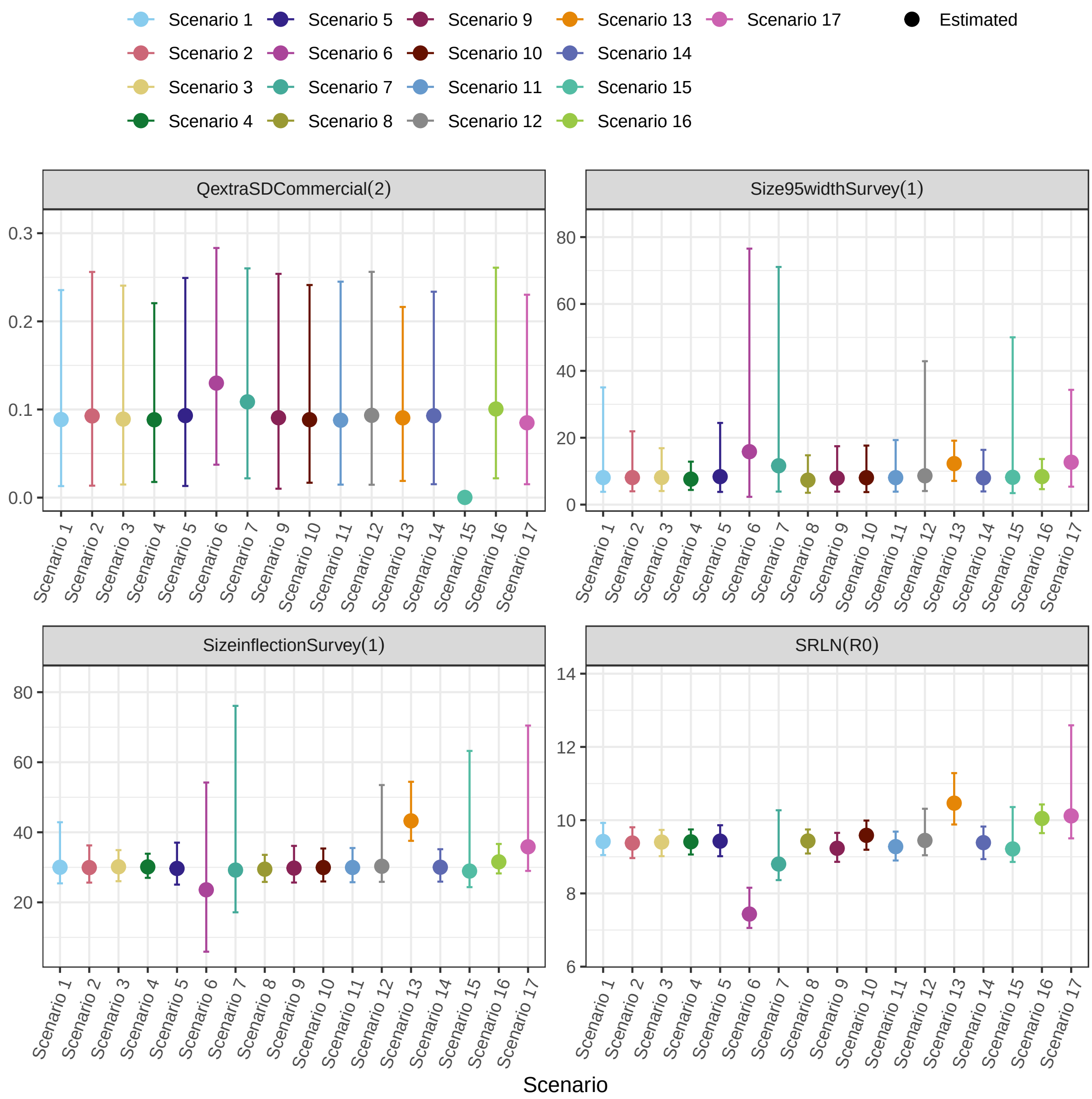


Figure F.2: Stock Synthesis sensitivity plots of estimated parameters for all scenarios for herrmanni curryfish.

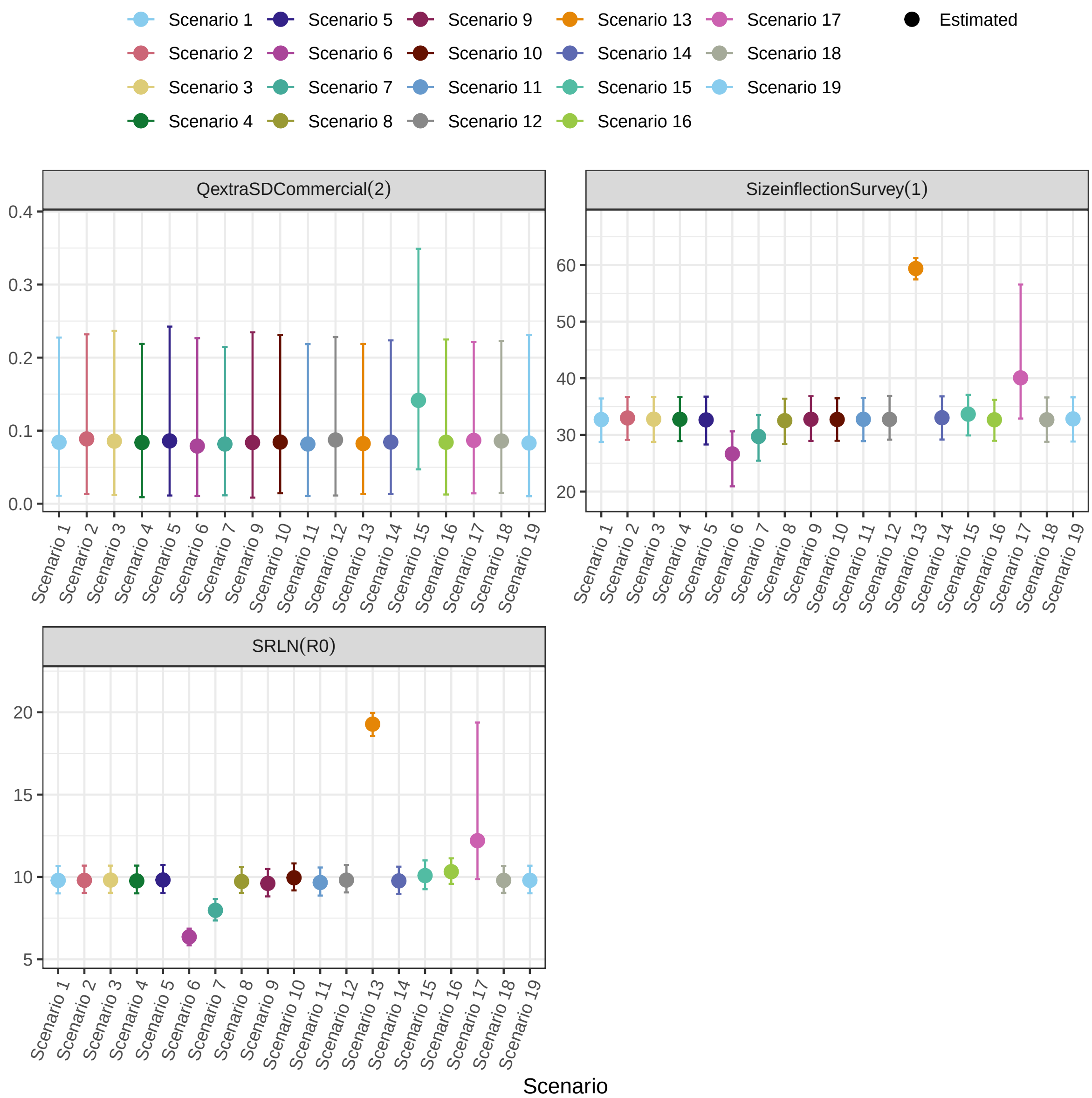


Figure F.3: Stock Synthesis sensitivity plots of estimated parameters for all scenarios for vastus curryfish.

F.2 Biomass

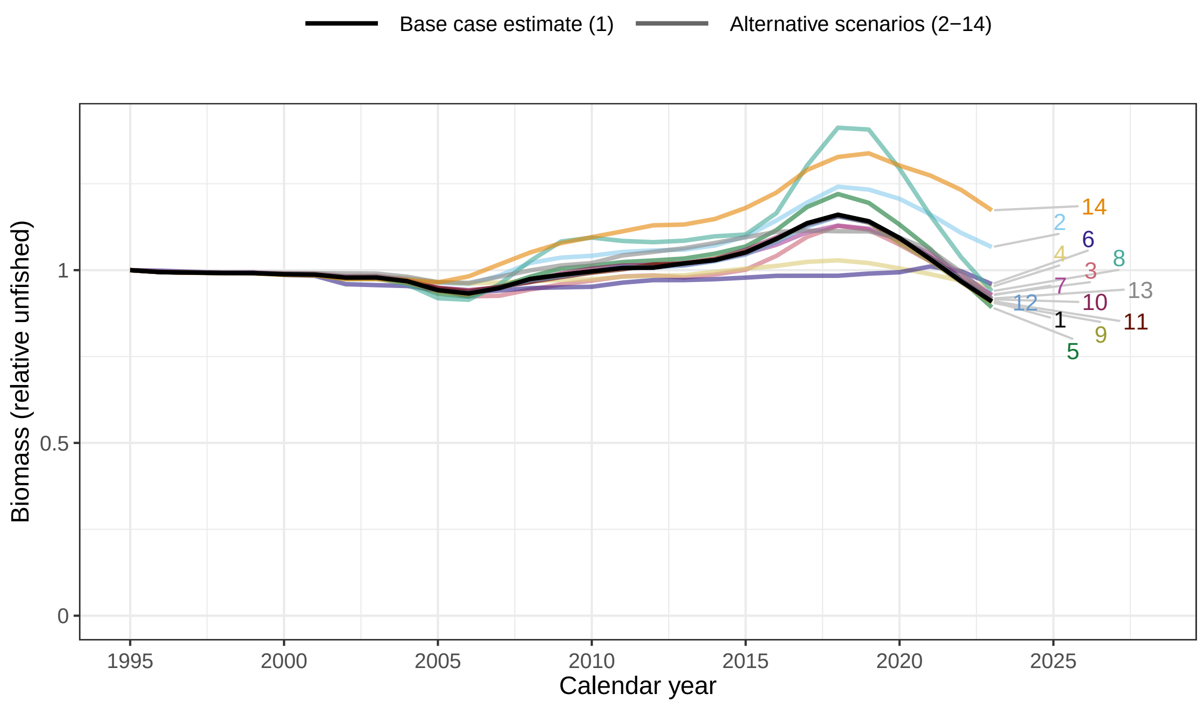


Figure F.4: MCMC predicted biomass trajectory relative to unfished for prickly redfish, from 1995 to 2023 for fourteen (out of fifteen) Stock Synthesis model scenarios.

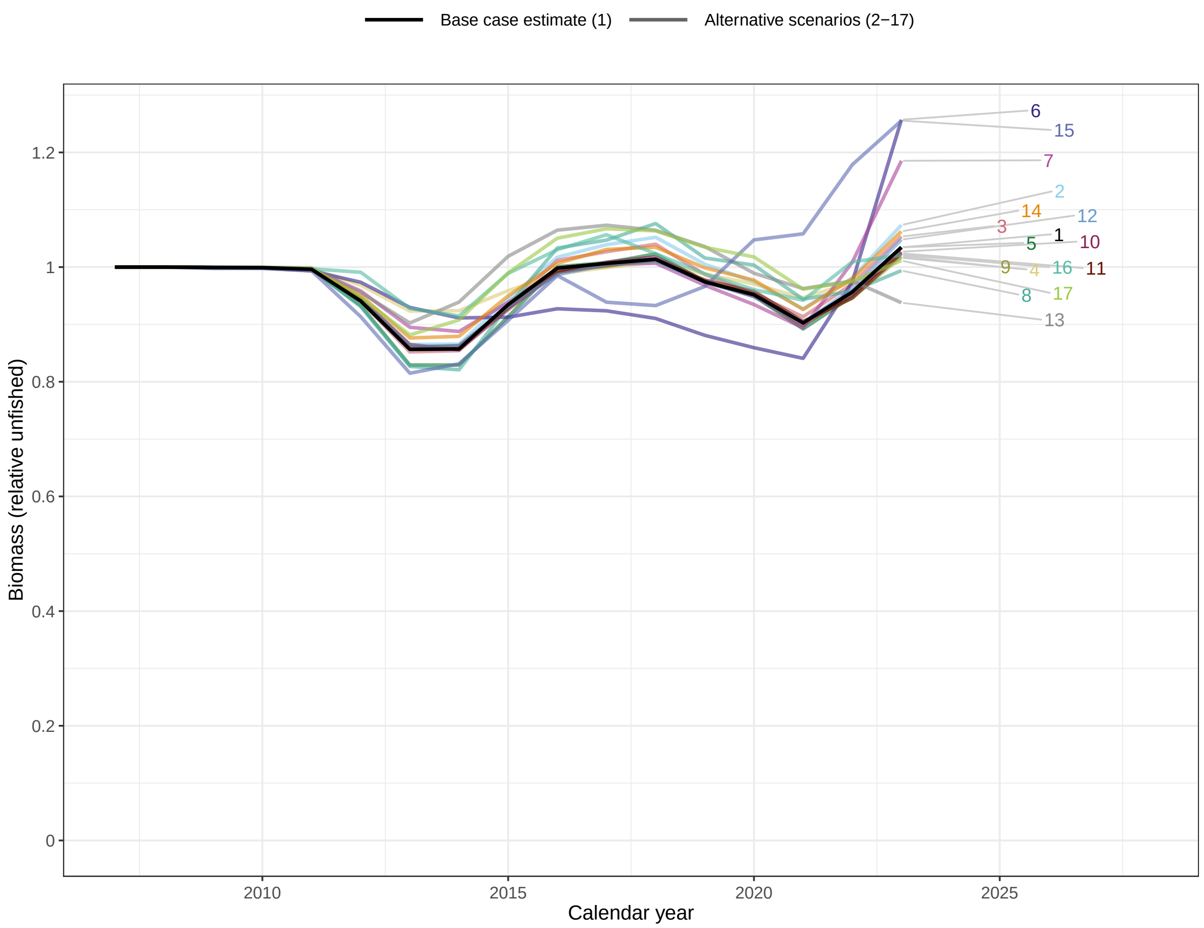


Figure F.5: MCMC predicted biomass trajectory relative to unfished for herrmanni curryfish, from 2007 to 2023 for all Stock Synthesis model scenarios.

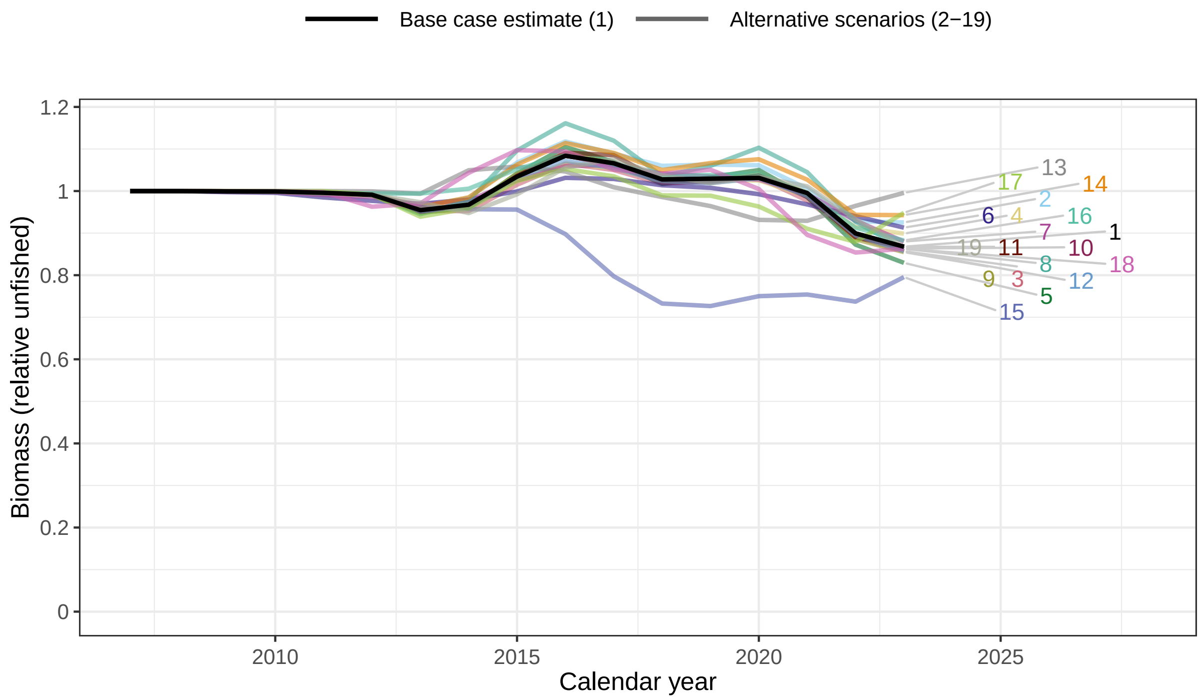


Figure F.6: MCMC predicted biomass trajectory relative to unfished for vastus curryfish, from 2007 to 2023 for all Stock Synthesis model scenarios.

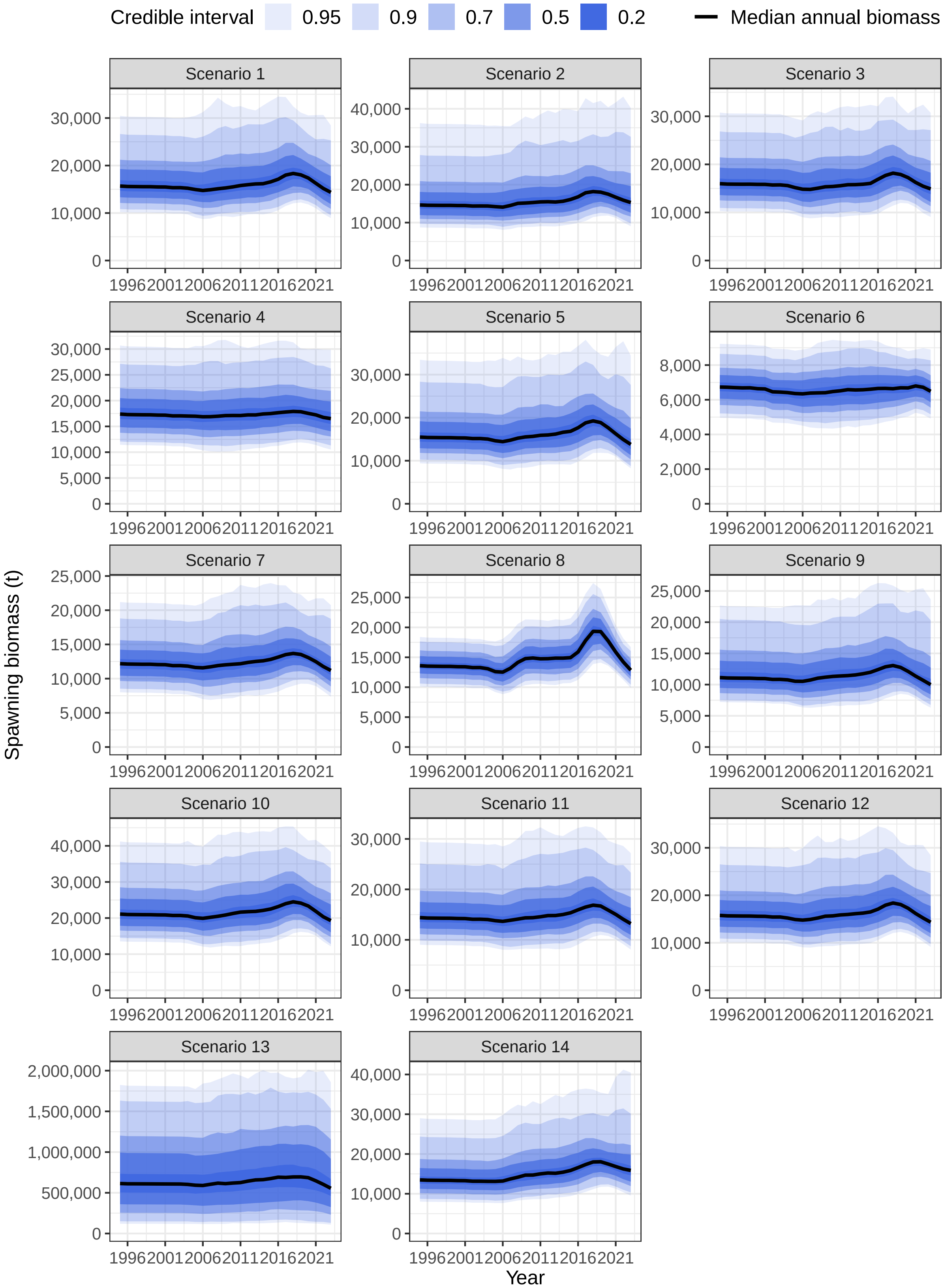


Figure F.7: MCMC predicted biomass trajectory relative to unfished for fourteen (out of fifteen) Stock Synthesis model scenarios for prickly redfish, from 1995 to 2023. Blue shading indicates the biomass Bayesian credibility interval.

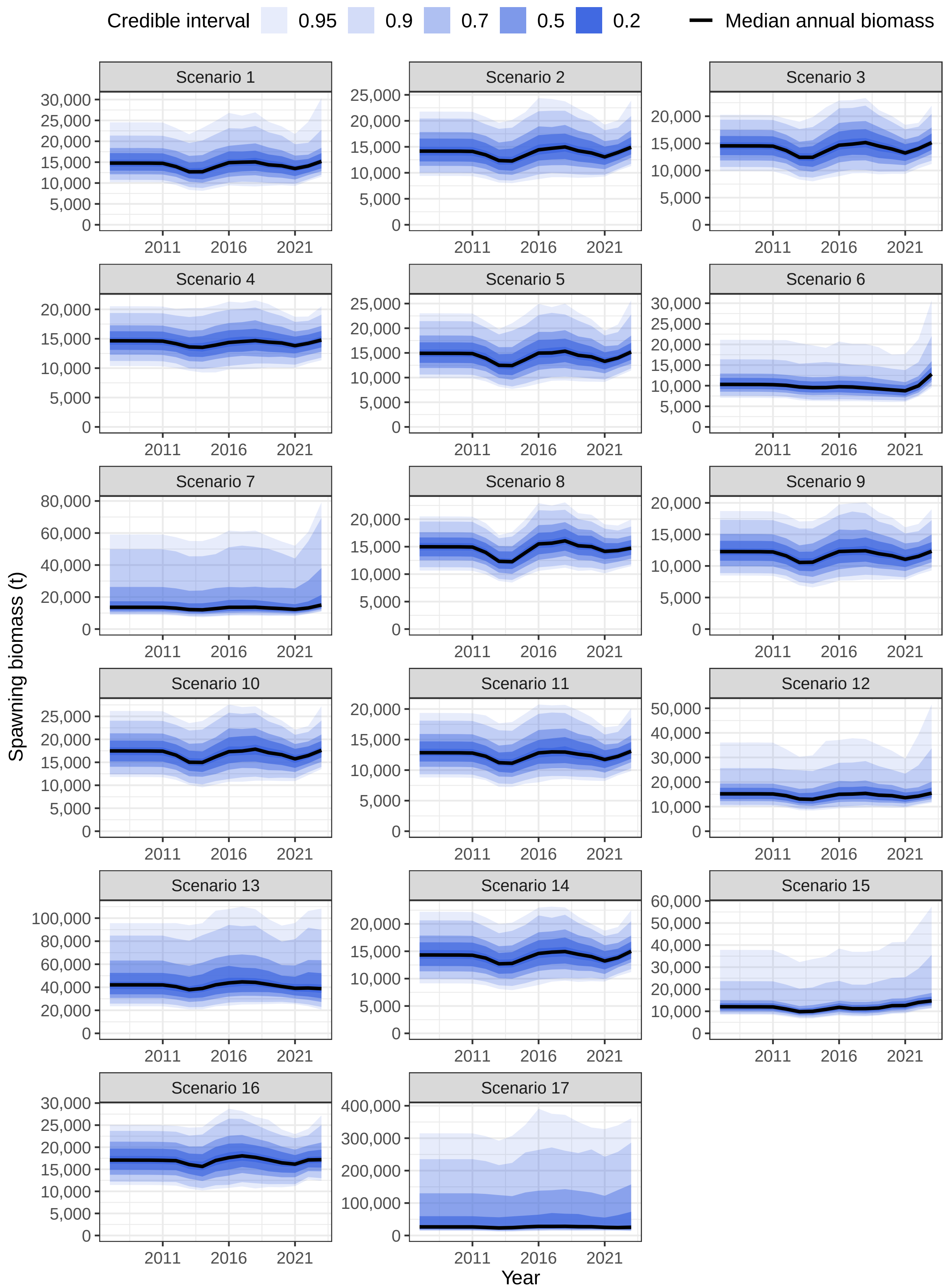


Figure F.8: MCMC predicted biomass trajectory relative to unfished for all Stock Synthesis model scenarios for herrmanni curryfish, from 1996 to 2023. Blue shading indicates the biomass Bayesian credibility interval.

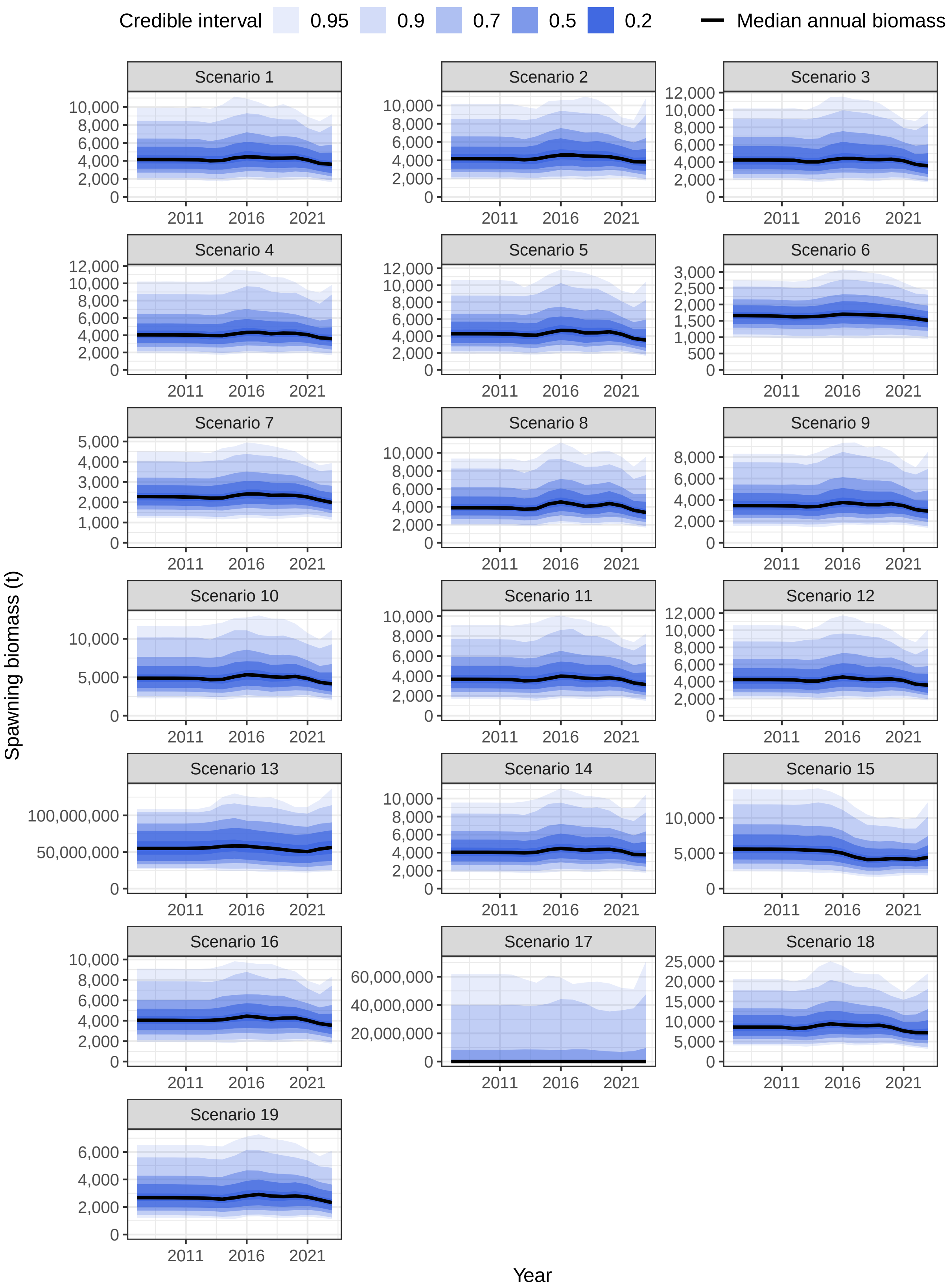


Figure F.9: MCMC predicted biomass trajectory relative to unfished for all Stock Synthesis model scenarios for vastus curryfish, from 1996 to 2023. Blue shading indicates the biomass Bayesian credibility interval.

F.3 Abundance indices

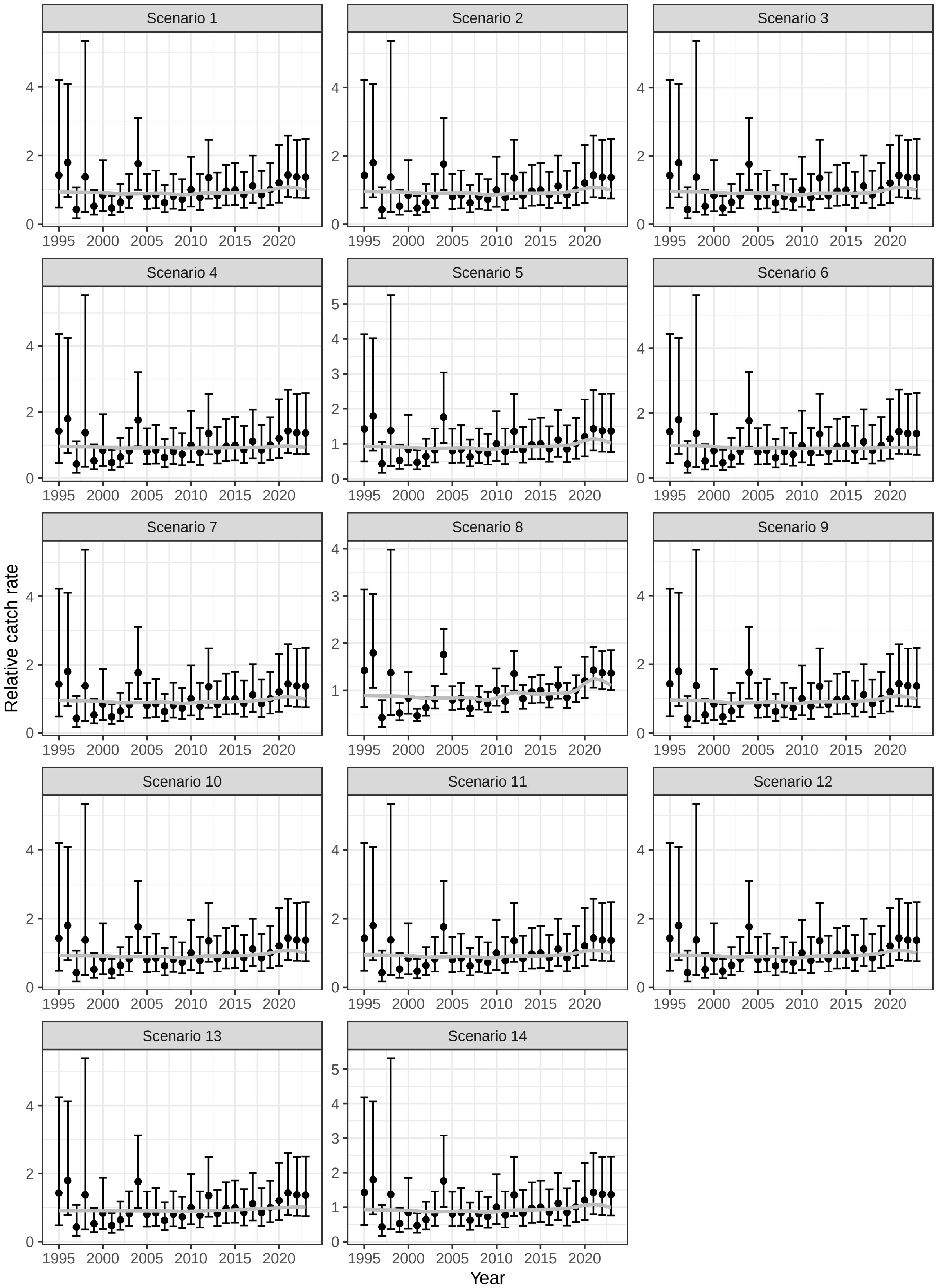


Figure F.10: Stock Synthesis model predictions (grey line) to commercial catch rates for prickly redfish, from 1995 to 2023 for fourteen (out of fifteen) Stock Synthesis sensitivity scenarios.

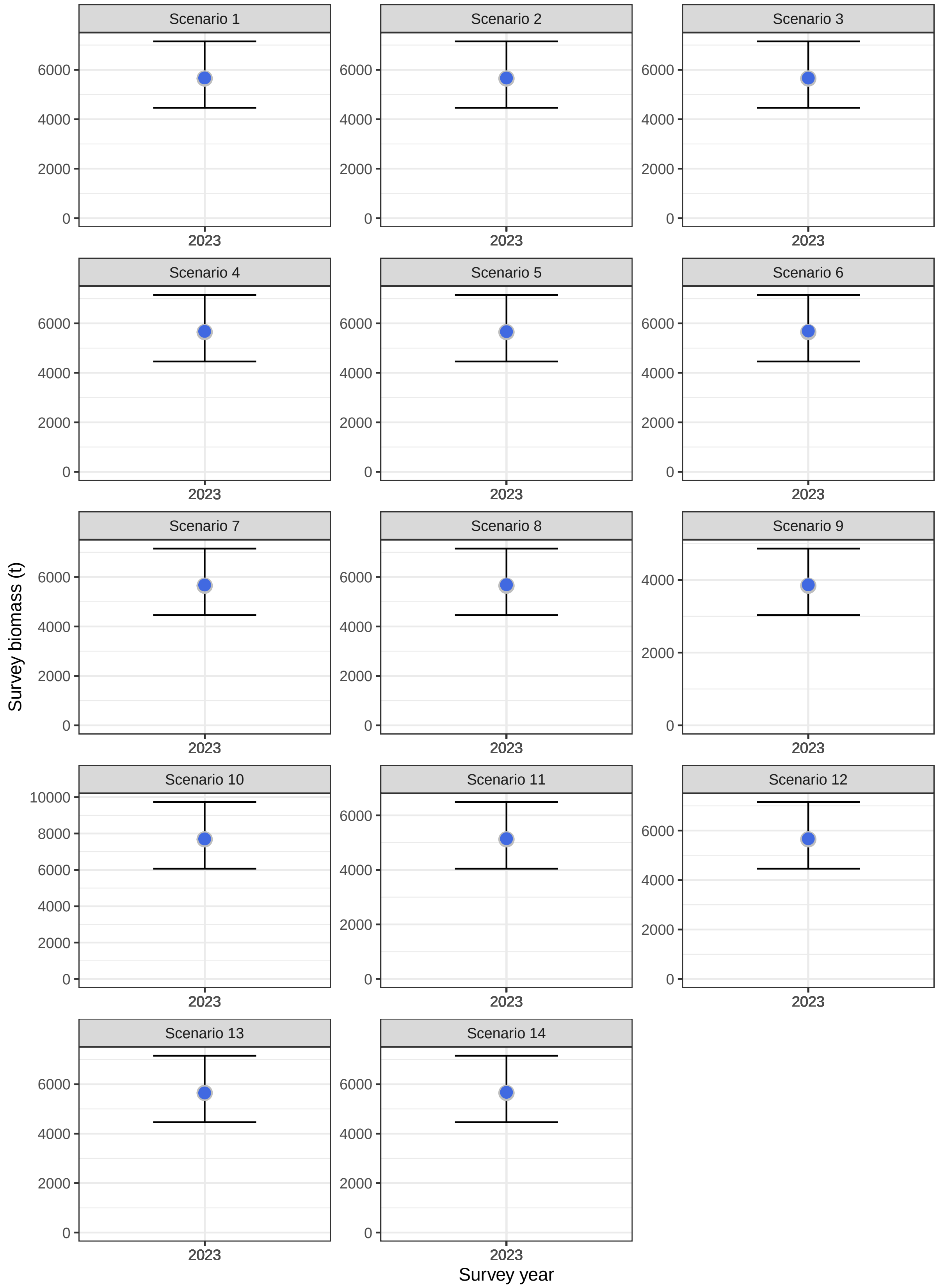


Figure F.11: Stock Synthesis model fit (blue dot) to survey estimated biomass (grey point with black error bars indicating the 95 percent CI of the estimate) for prickly redfish for fourteen (out of fifteen) Stock Synthesis sensitivity scenarios.

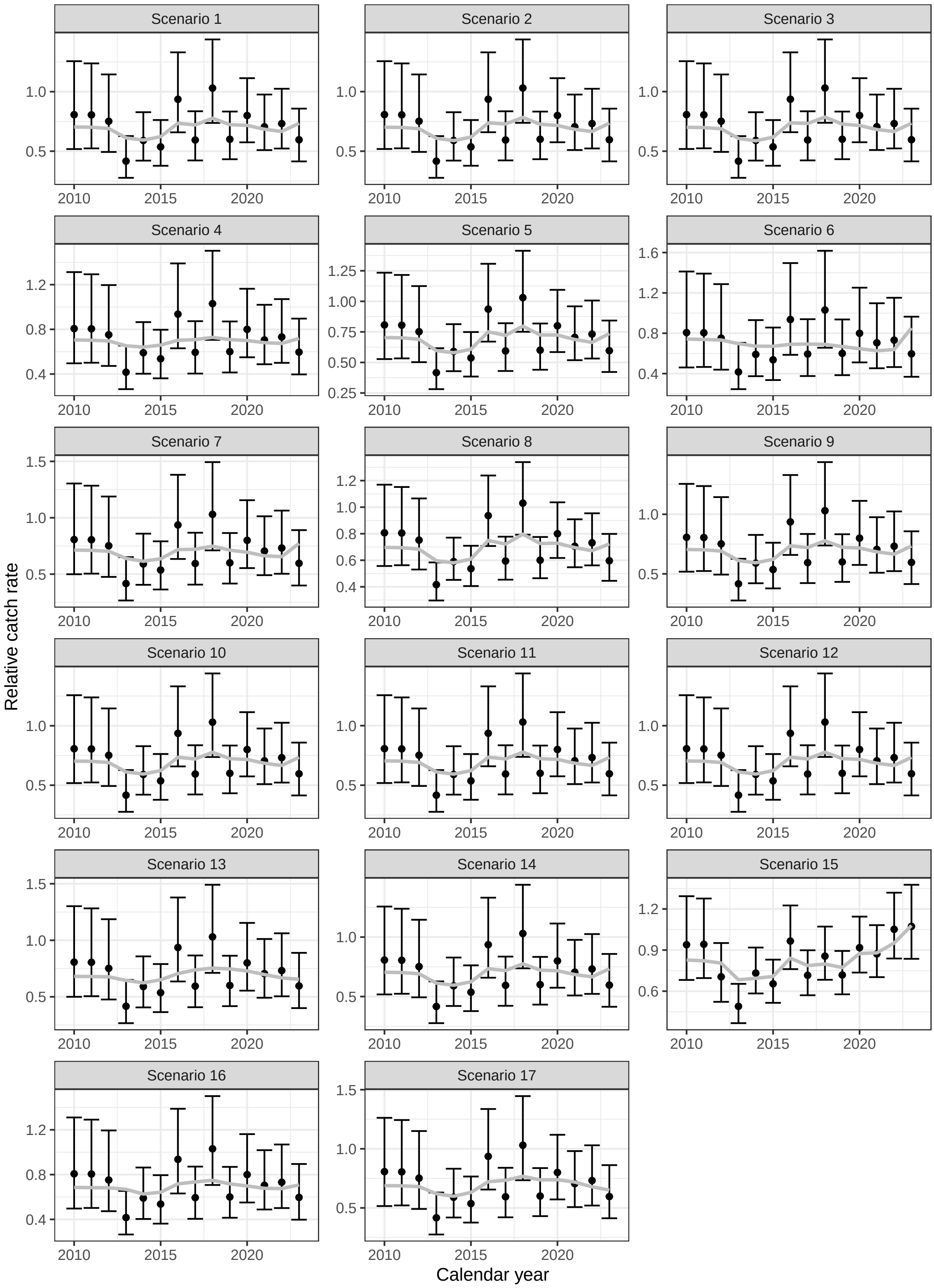


Figure F.12: Stock Synthesis model predictions (grey line) to commercial catch rates for herrmanni curryfish, from 2010 to 2023 for all Stock Synthesis sensitivity scenarios.

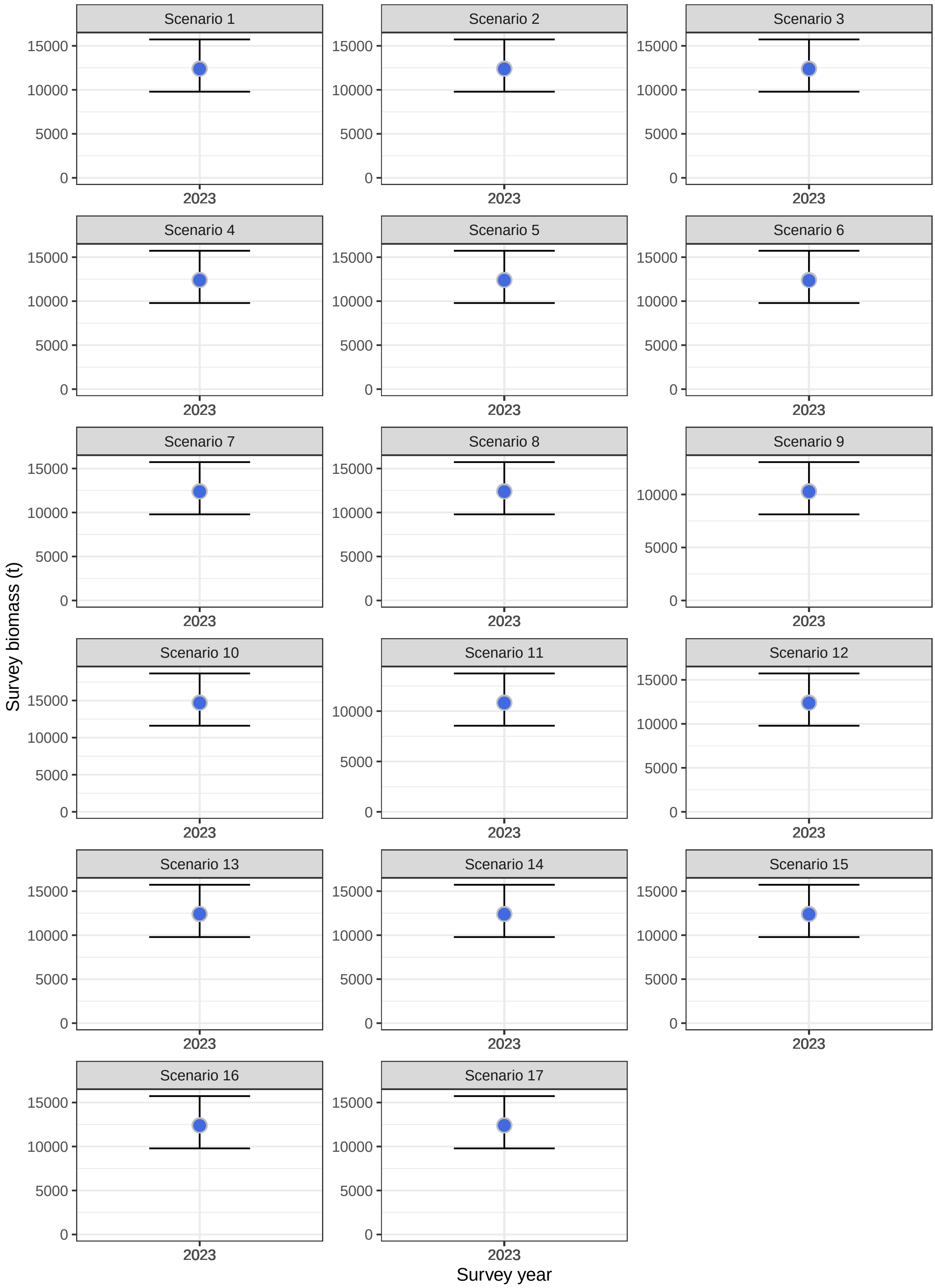


Figure F.13: Stock Synthesis model fit (blue dot) to survey estimated biomass (grey point with black error bars indicating the 95 percent CI of the estimate) for herrmanni curryfish for all Stock Synthesis sensitivity scenarios.

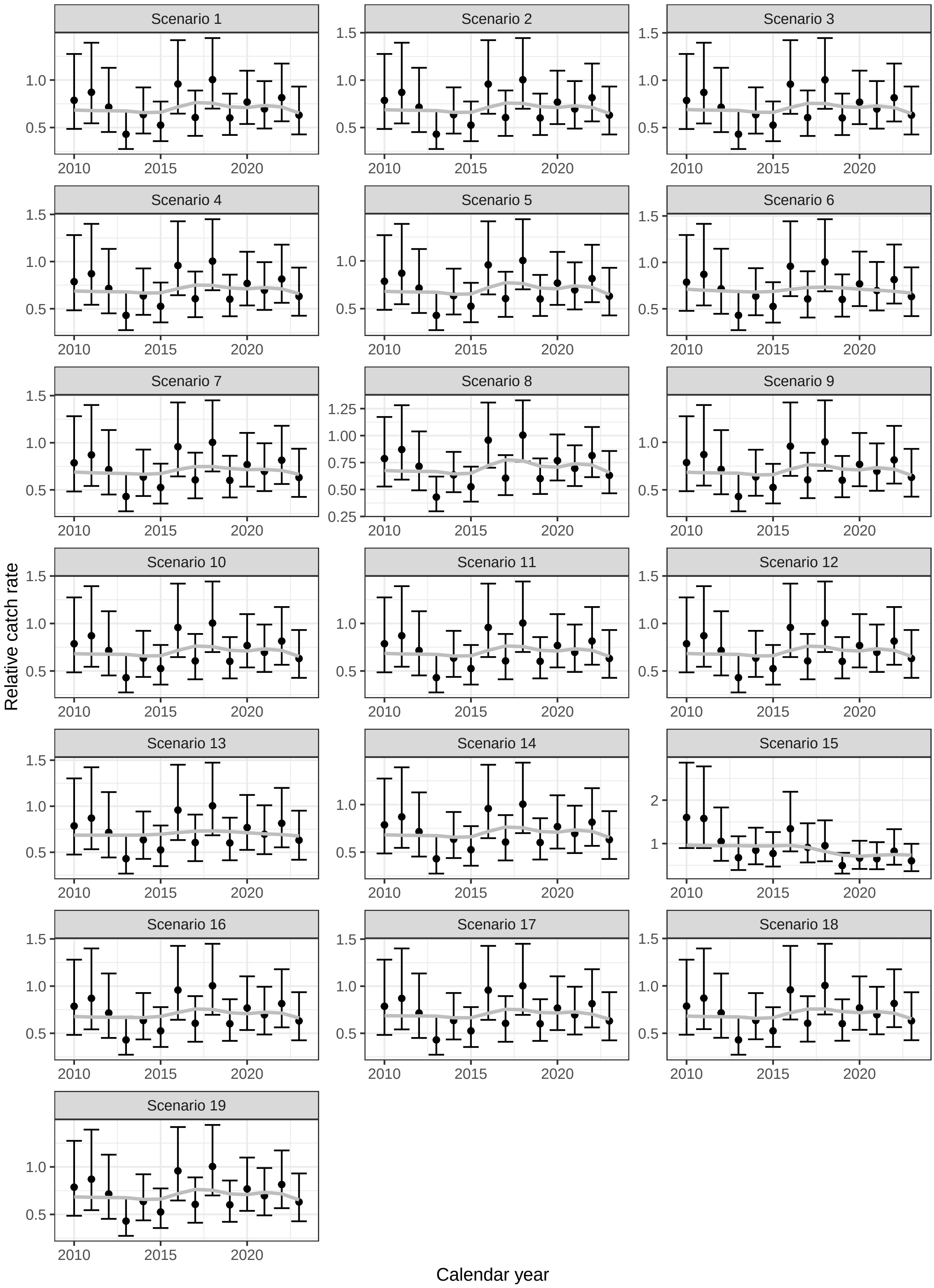


Figure F.14: Stock Synthesis model predictions (blue line) to commercial catch rates for vastus curryfish, from 2010 to 2023 for all Stock Synthesis sensitivity scenarios.

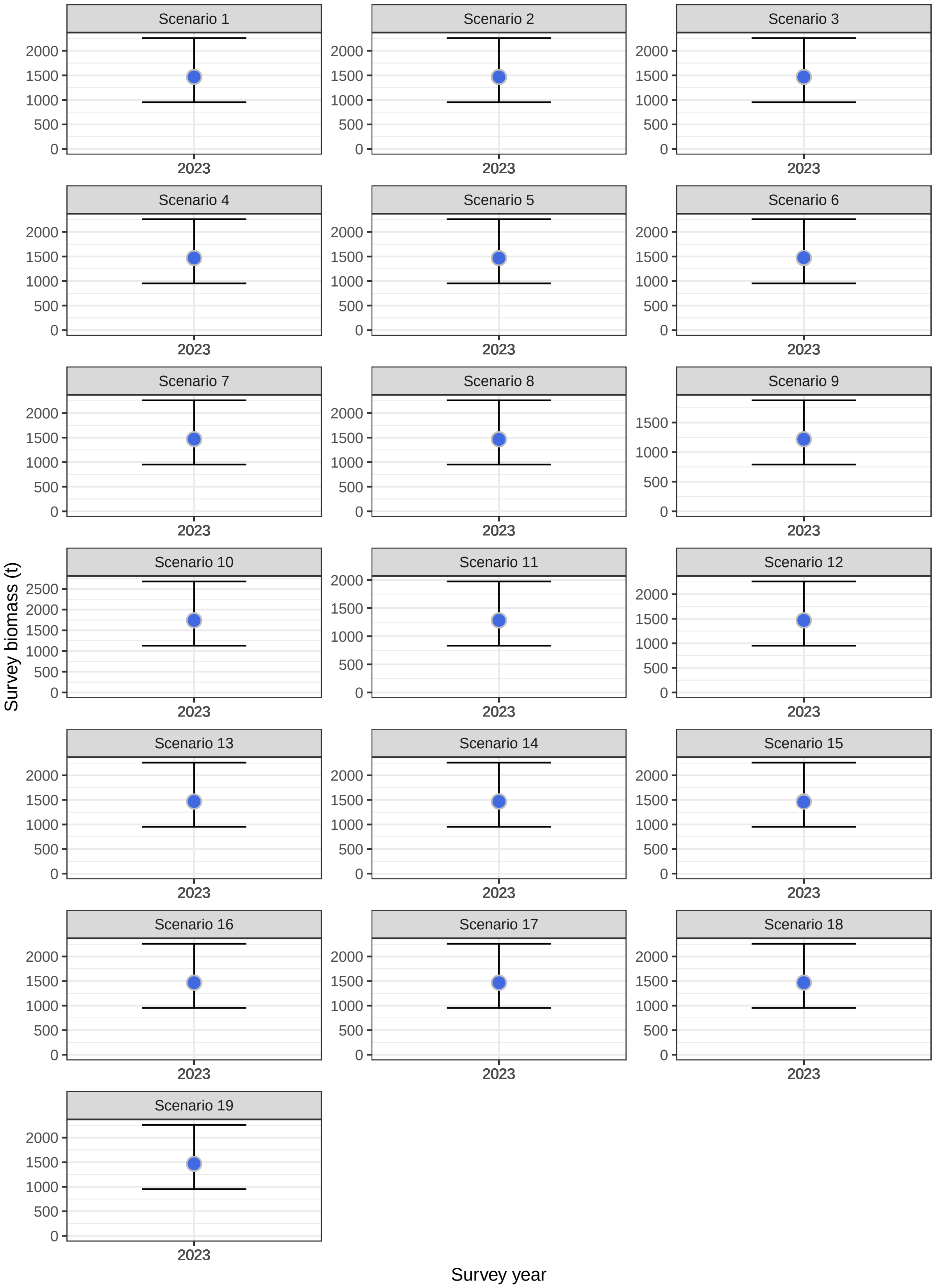


Figure F.15: Stock Synthesis model fit (blue dot) to survey estimated biomass (grey point with black error bars indicating the 95 percent CI of the estimate) for vastus curryfish for all Stock Synthesis sensitivity scenarios.

F.4 Length composition

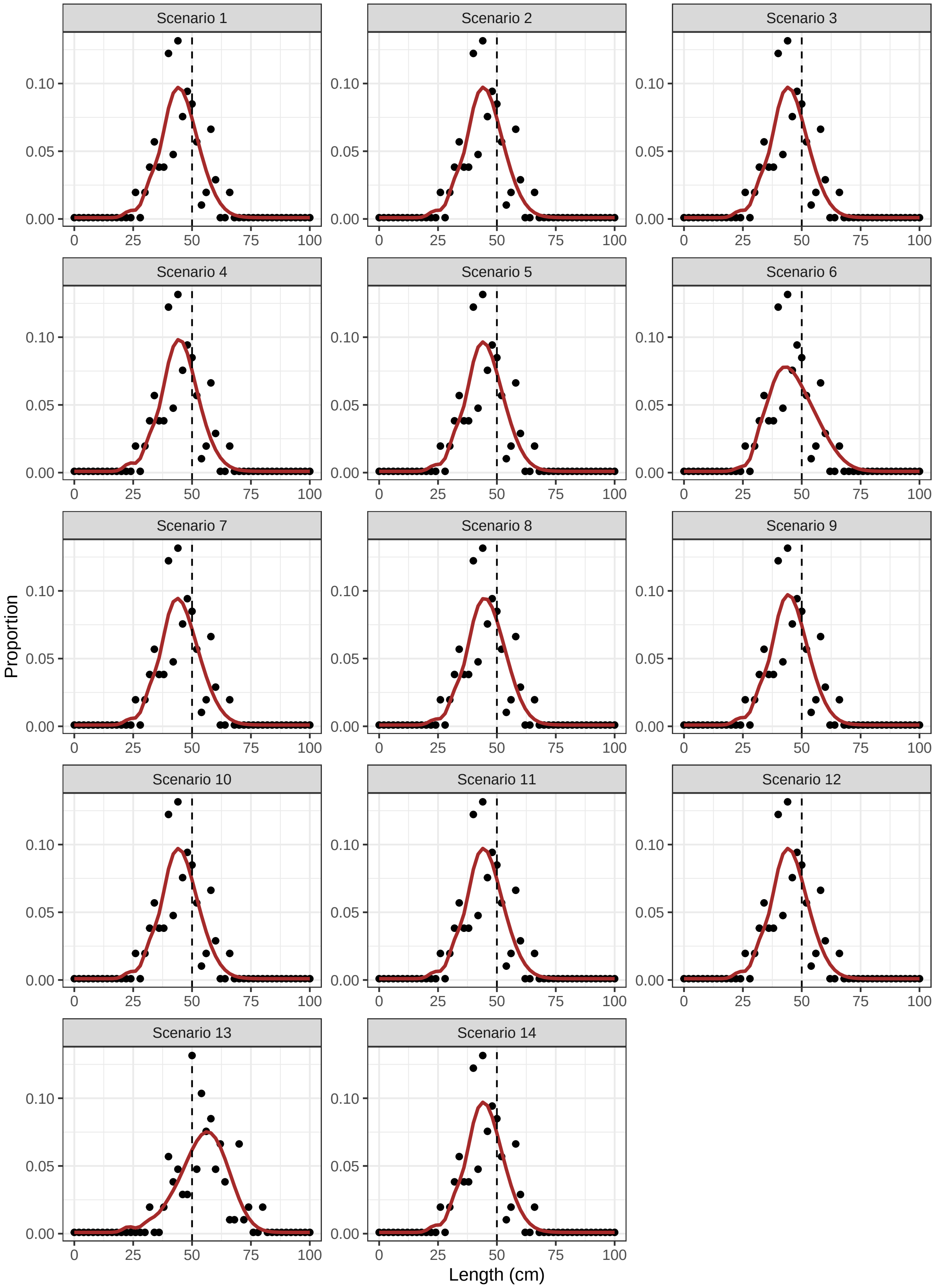


Figure F.16: Fits to length structures (brown line) for the survey fleet for prickly redfish for fourteen (out of fifteen) Stock Synthesis sensitivity scenarios. The dashed vertical line indicates the MLS of 50 cm.

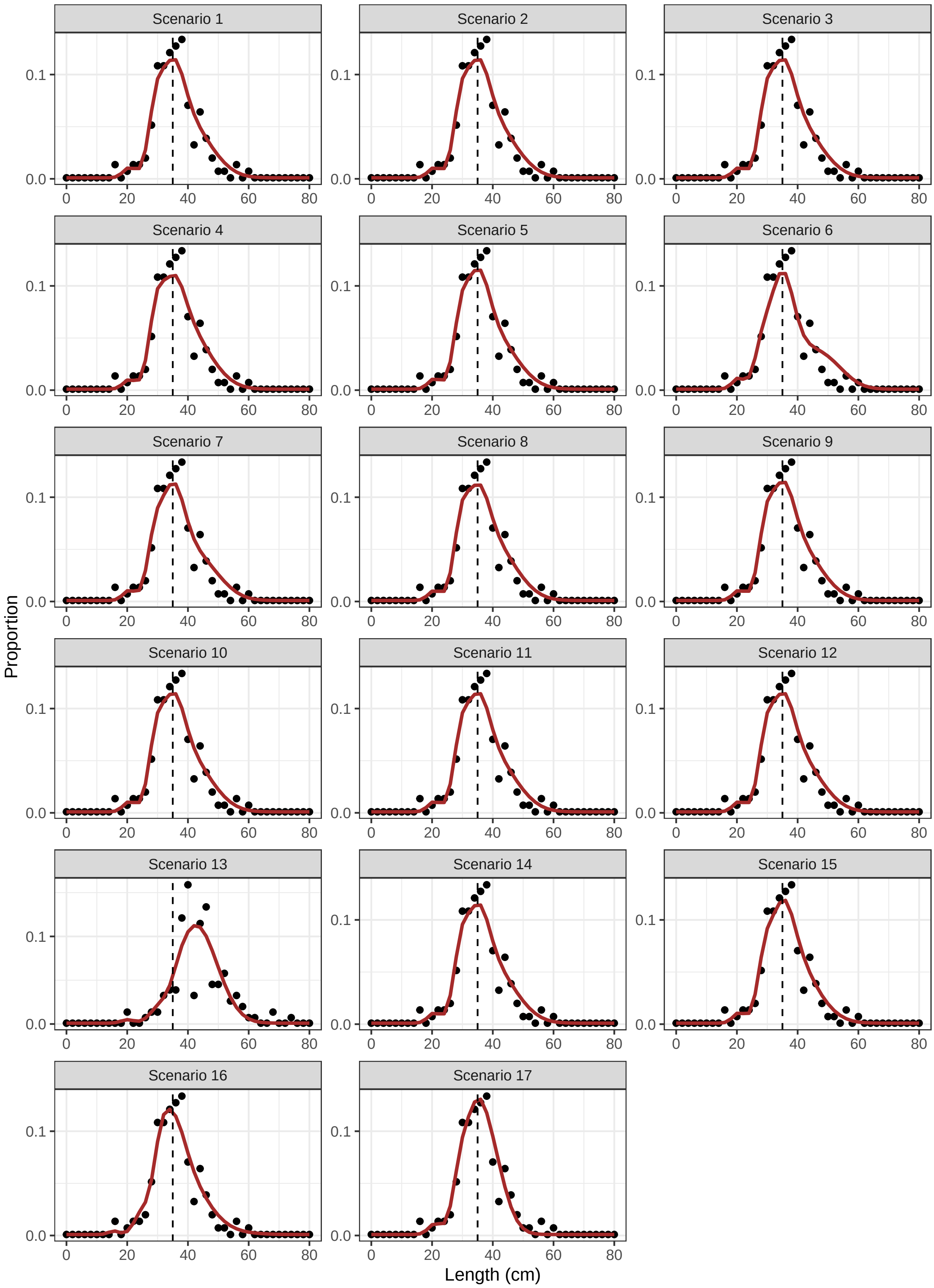


Figure F.17: Fits to length structures (brown line) for the survey fleet for herrmanni curryfish for all Stock Synthesis sensitivity scenarios. The dashed vertical line indicates the MLS of 35 cm.

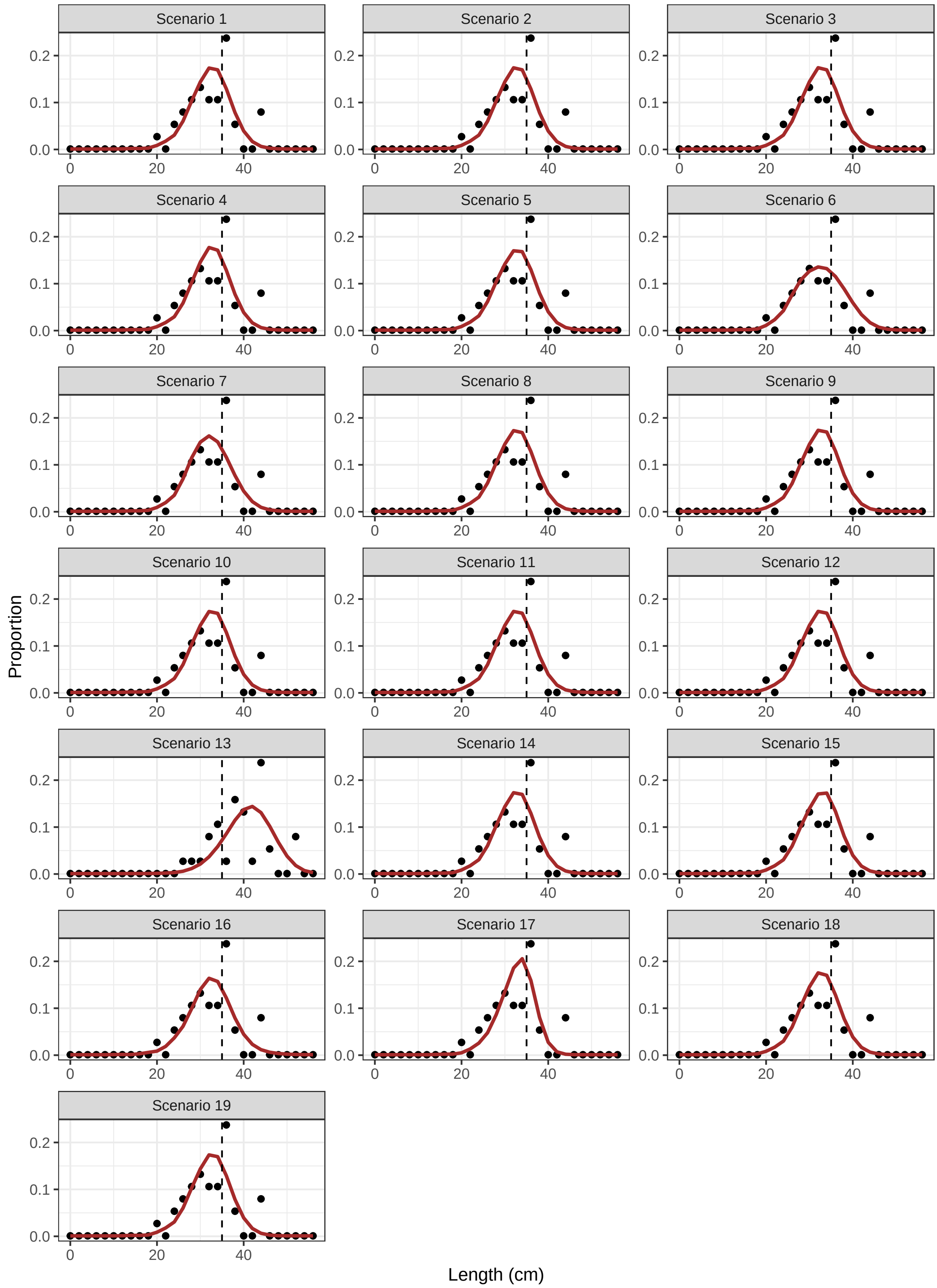


Figure F.18: Stock Synthesis model fit (brown line) to length structures for the 2023 survey for vastus curryfish for all Stock Synthesis sensitivity scenarios. The dashed vertical line indicates the MLS of 35 cm.

F.5 Stock Recruitment curve

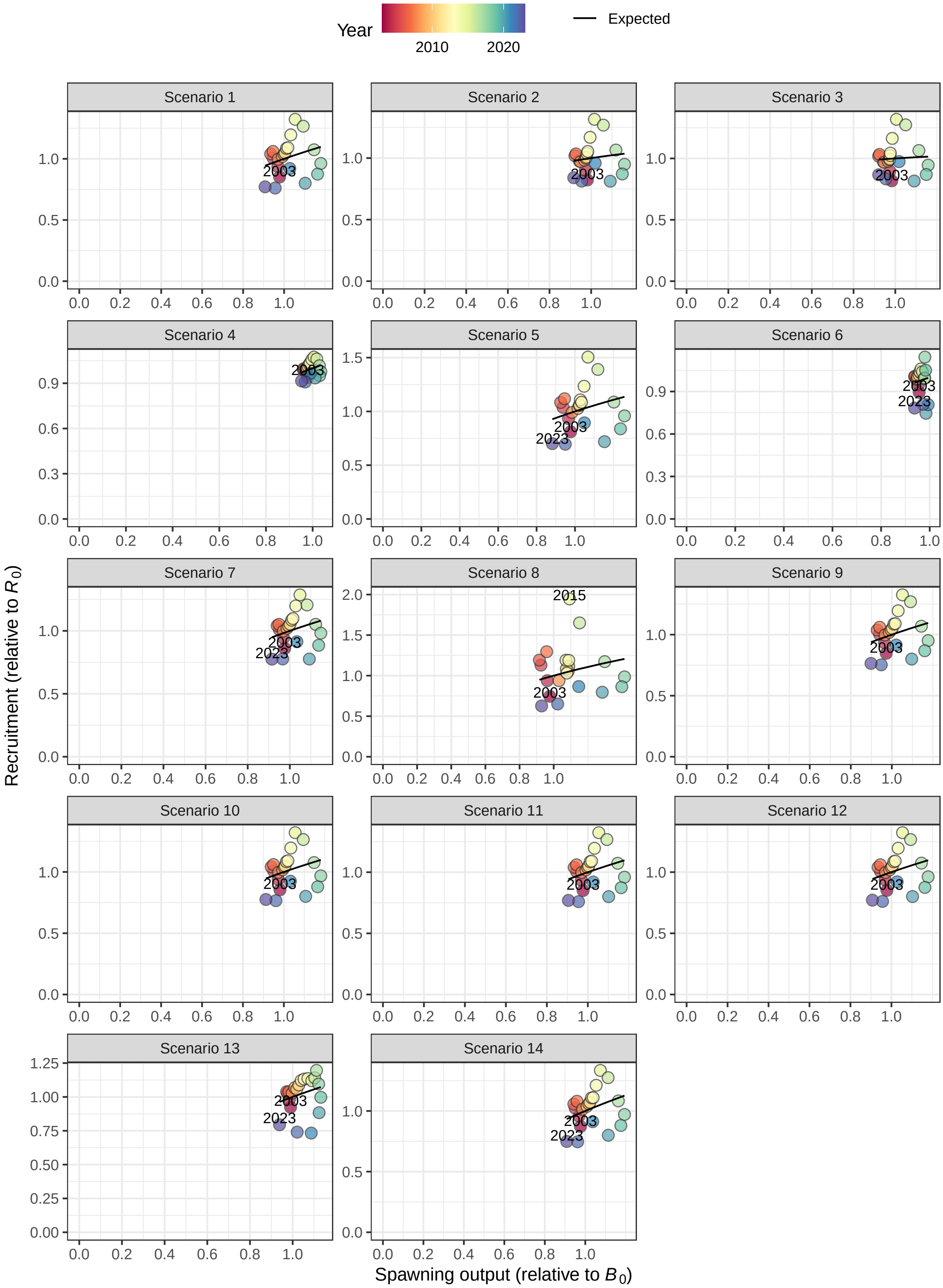


Figure F.19: Stock-recruitment curve for fourteen (out of fifteen) sensitivity scenarios conducted for prickly redfish Stock Synthesis model. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

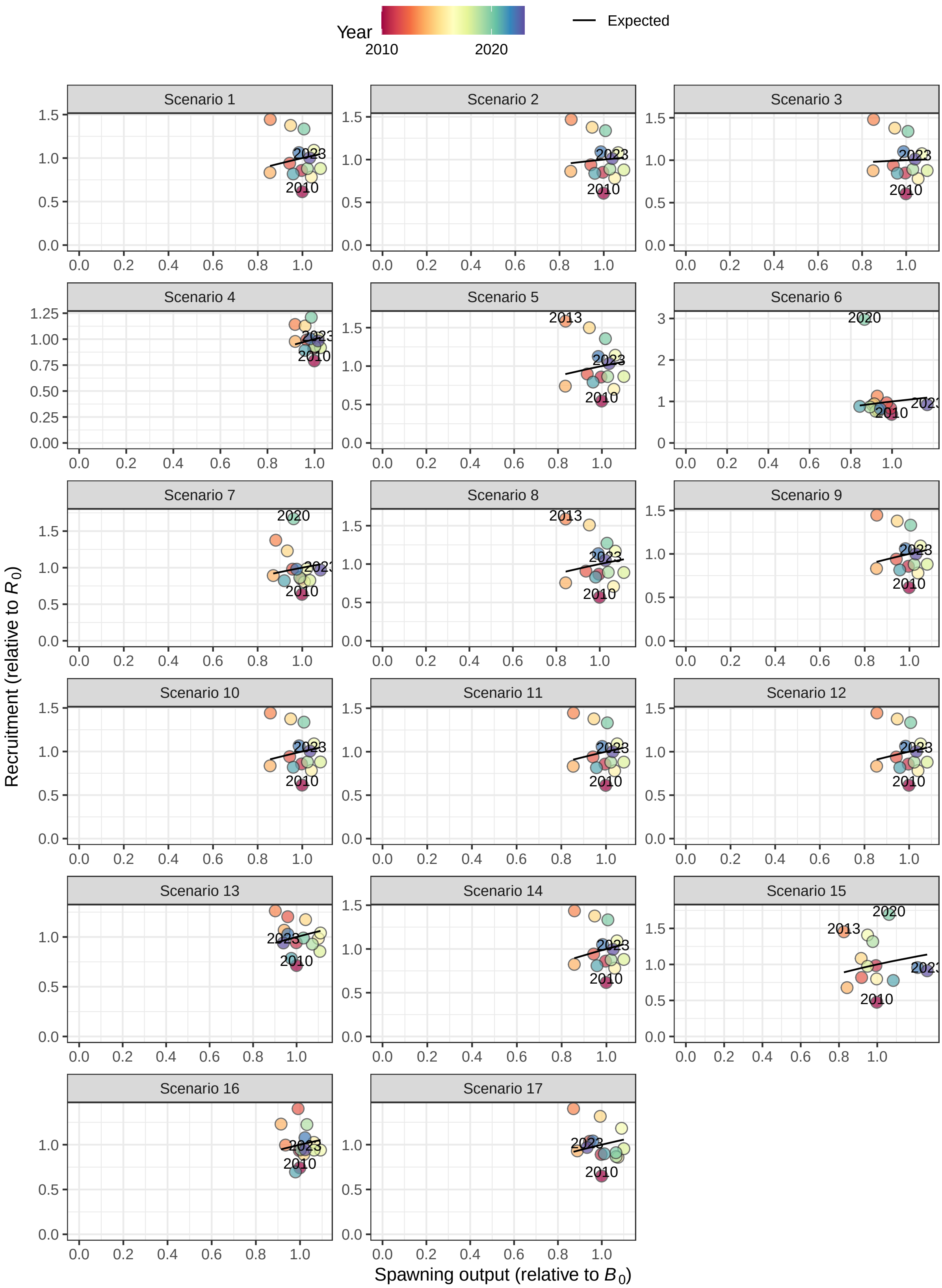


Figure F.20: Stock-recruitment curve for all sensitivity scenarios conducted for herrmanni curryfish Stock Synthesis model. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

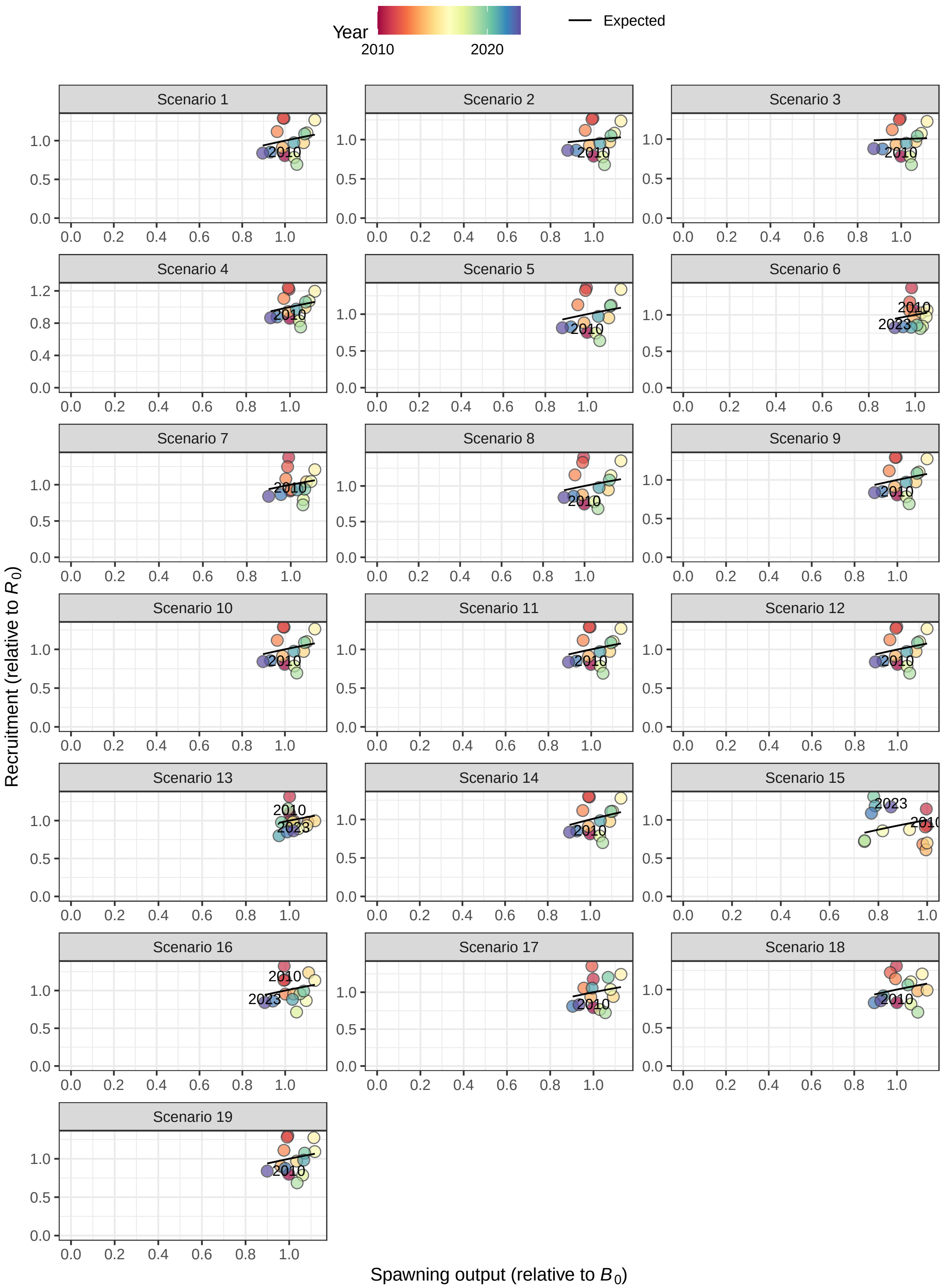


Figure F.21: Stock-recruitment curve for all sensitivity scenarios conducted for vastus curryfish Stock Synthesis model. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

F.6 Recruitment deviations

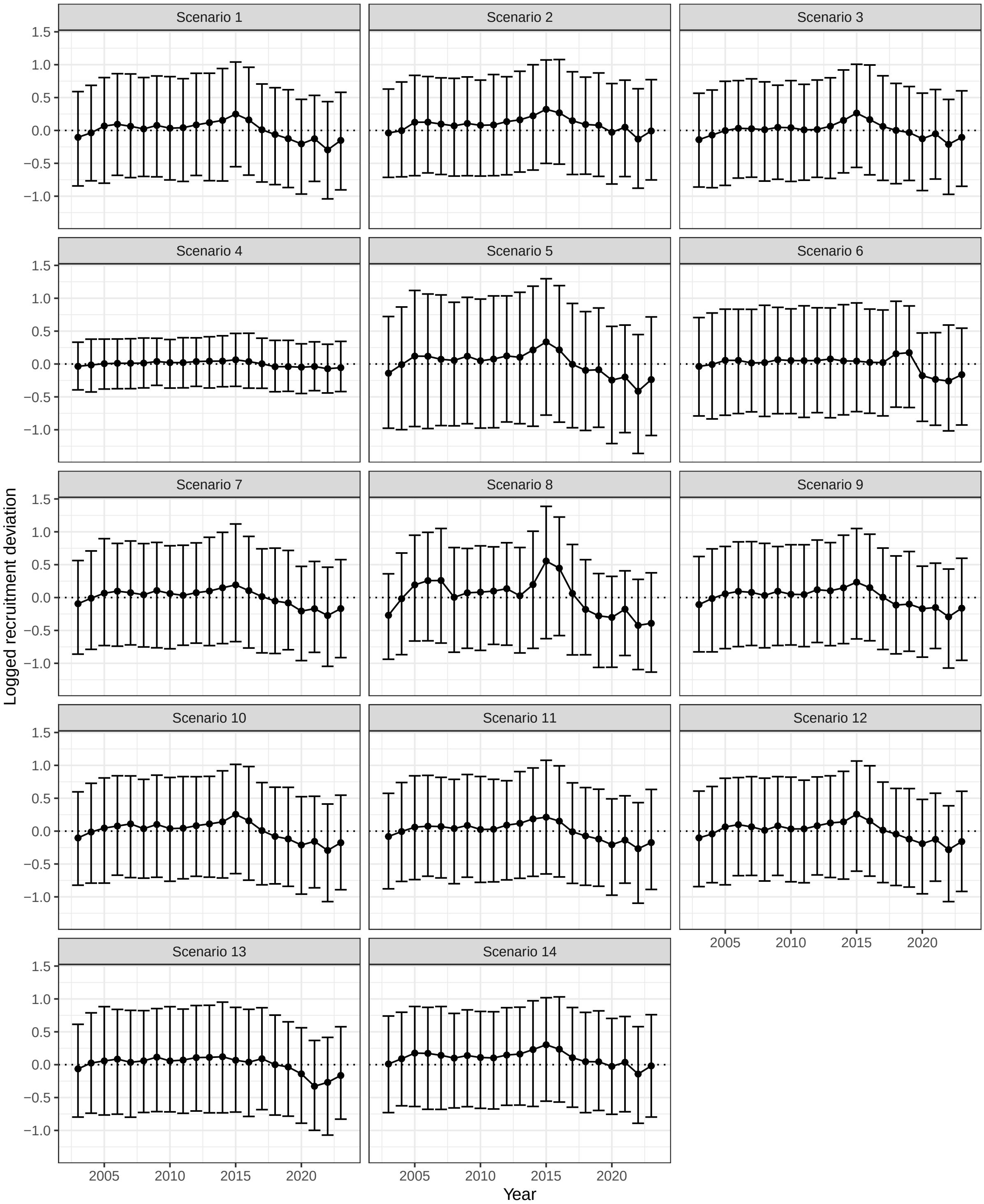


Figure F.22: Recruitment deviations for the fourteen (out of fifteen) sensitivity scenarios conducted for prickly redfish Stock Synthesis model, from 2003 to 2023.

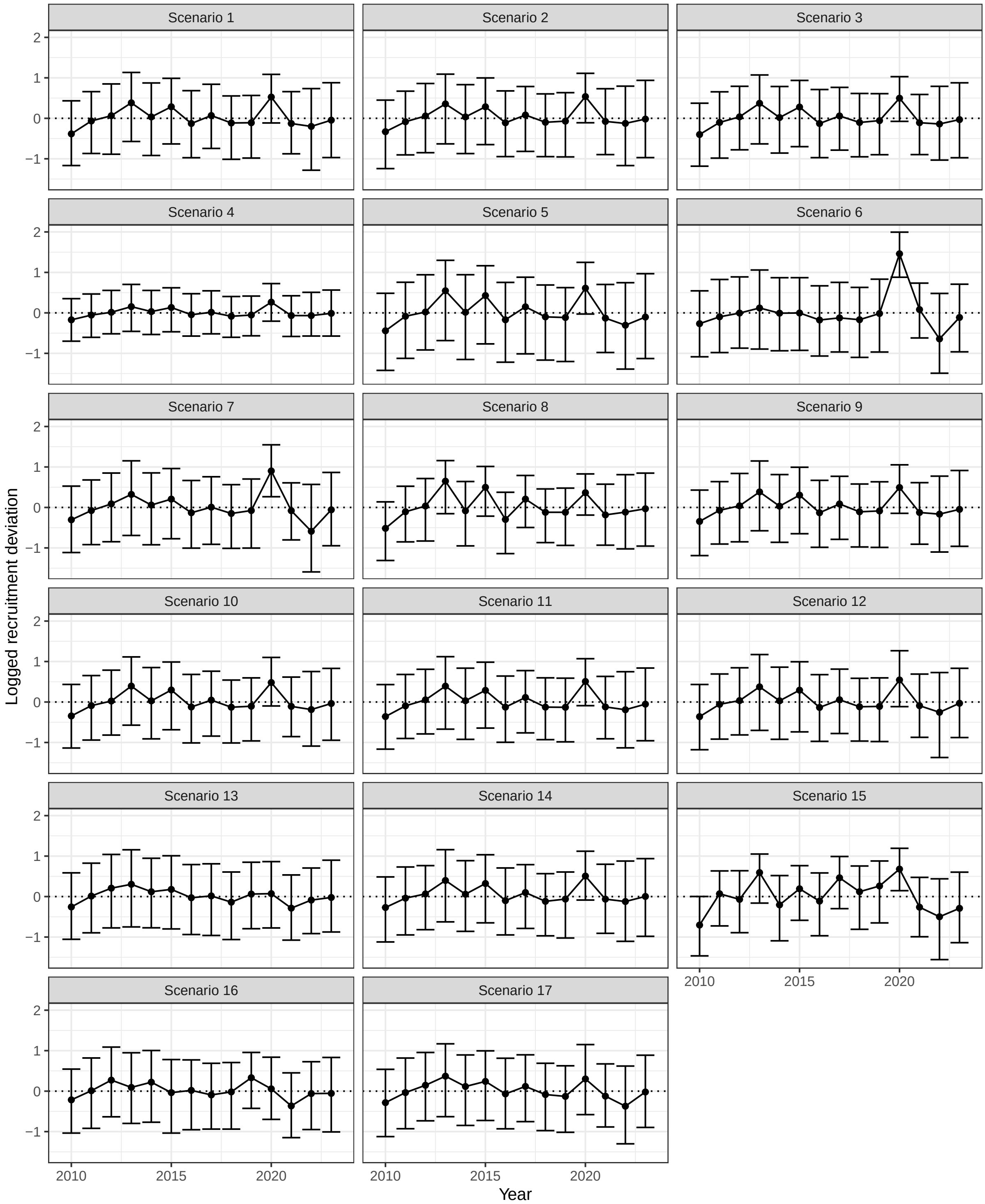


Figure F.23: Recruitment deviations for all sensitivity scenarios conducted for herrmanni curryfish Stock Synthesis model, from 2010 to 2023.

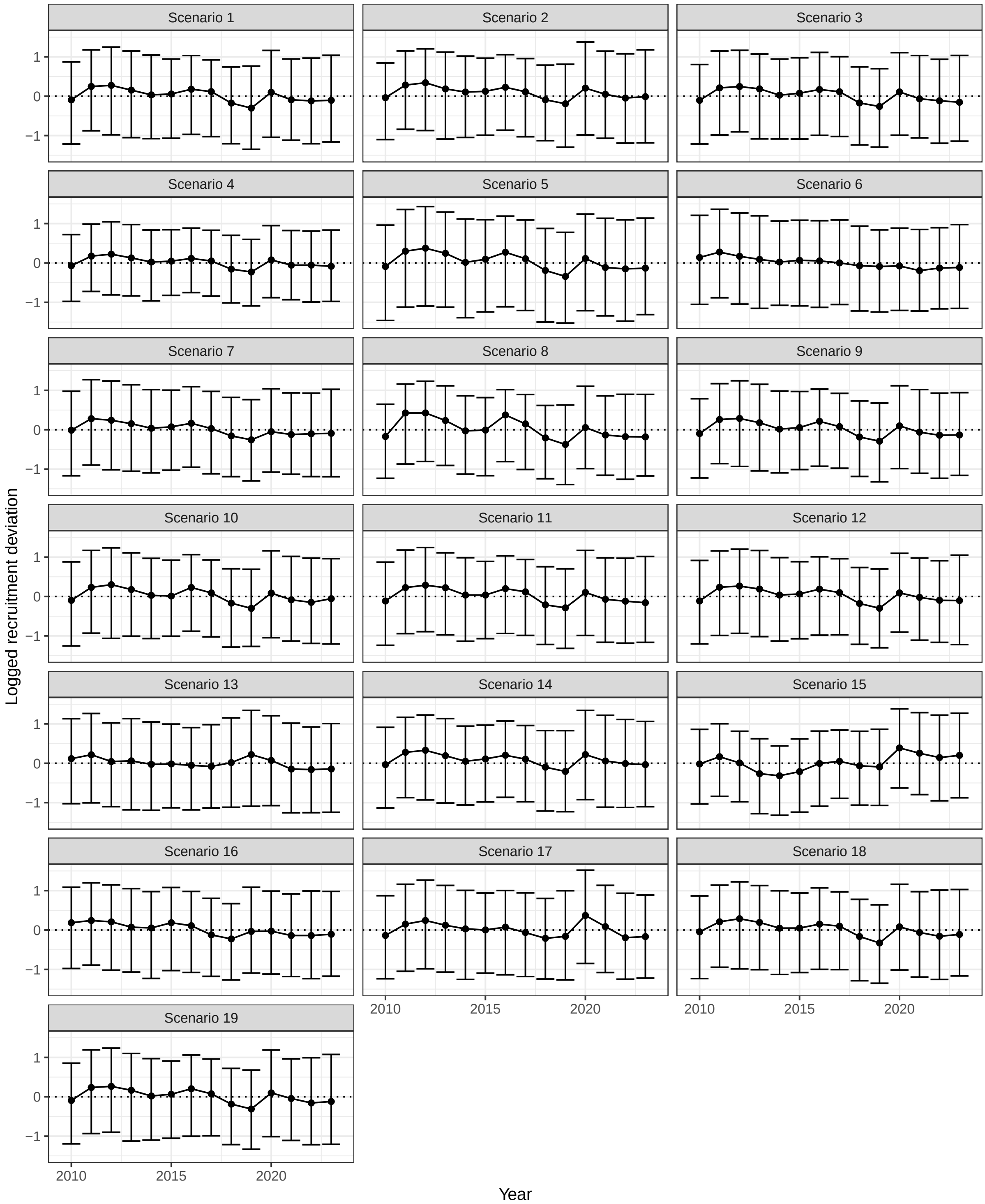


Figure F.24: Recruitment deviations for all sensitivity scenarios conducted for vastus curryfish Stock Synthesis model, from 2010 to 2023.

F.7 Fishing mortality

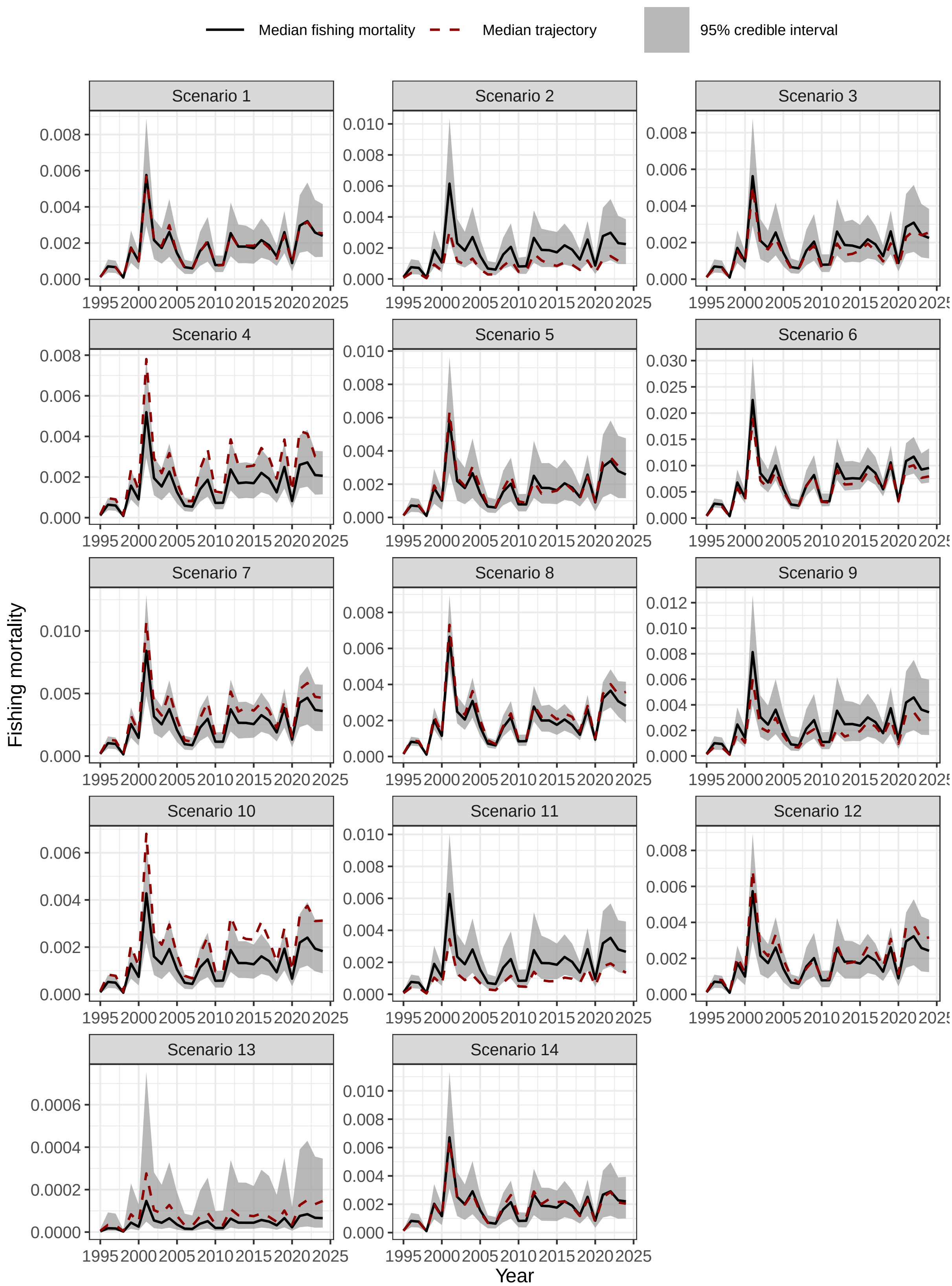


Figure F.25: Predicted fishing mortality (F) for the legal-size biomass for fourteen (out of fifteen) sensitivity scenarios conducted for prickly redfish, from 1995 to 2023.

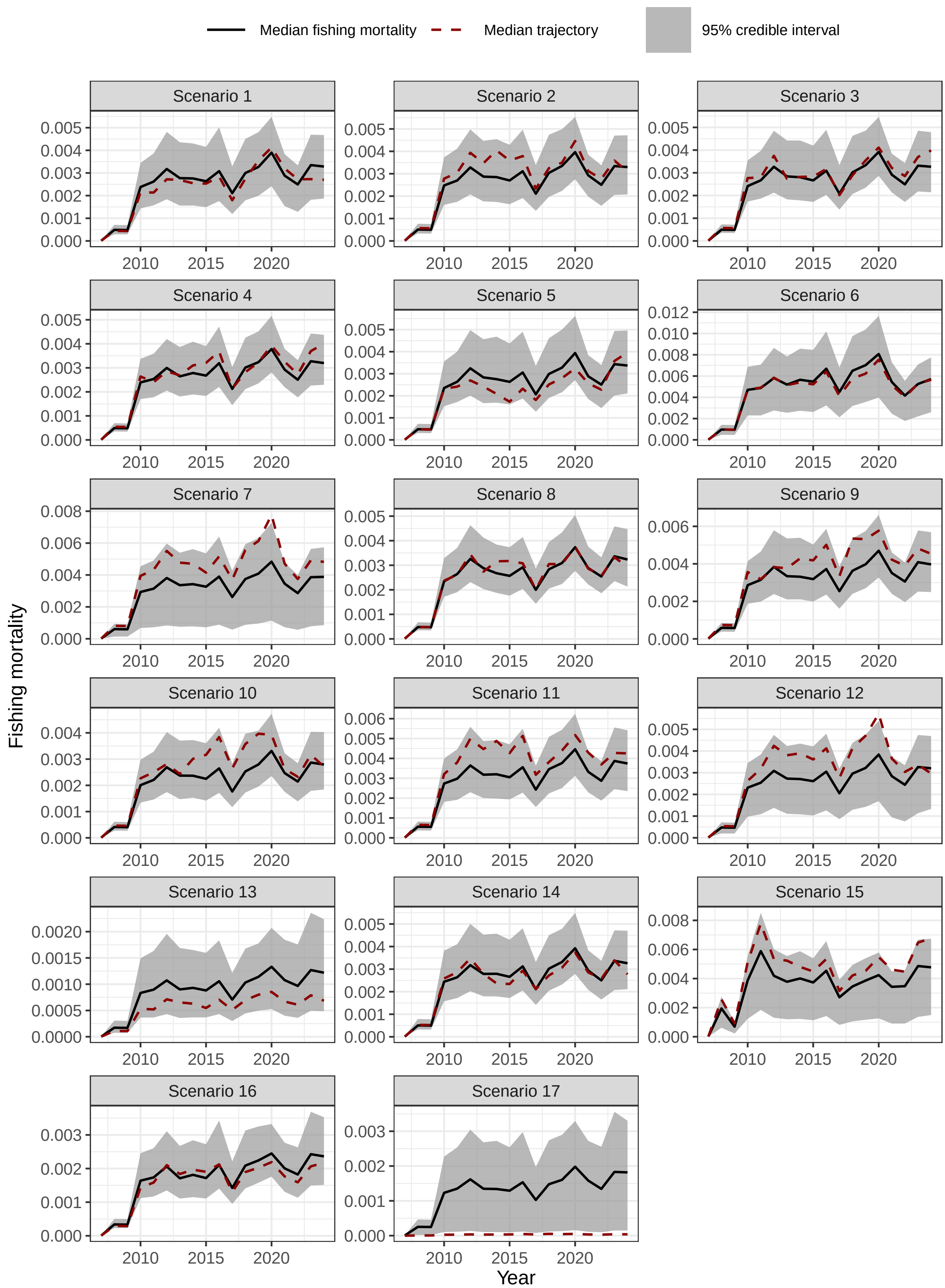


Figure F.26: Predicted fishing mortality (F) for the legal-size biomass for all sensitivity scenarios conducted for herrmanni curryfish, from 2007 to 2023.

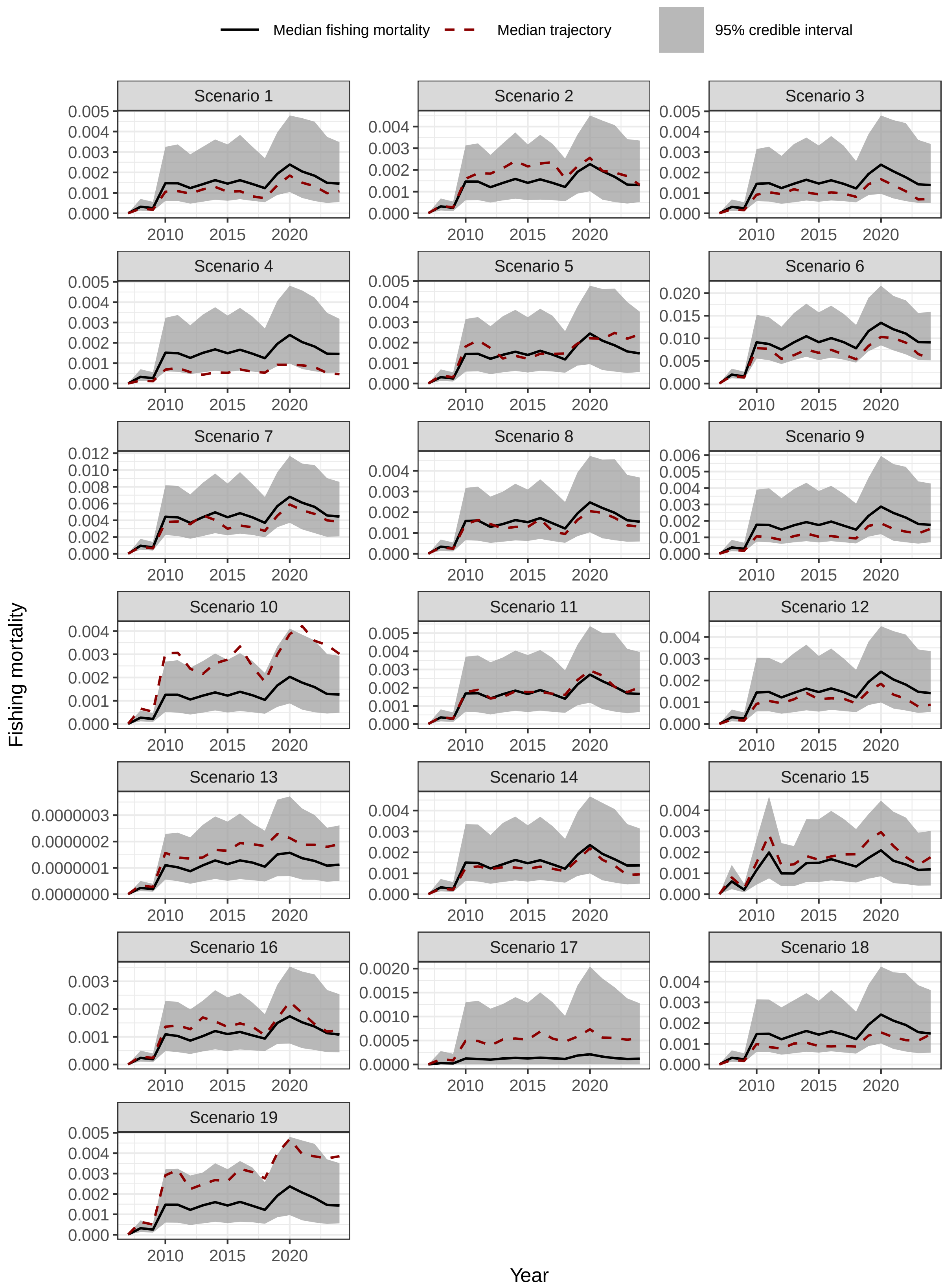


Figure F.27: Predicted fishing mortality (F) for the legal-size biomass for all sensitivity scenarios conducted for vastus curryfish, from 2007 to 2023.

F.8 Prickly redfish depletion before 1940

Given market acceptance and accessibility to fishing by free divers, prickly redfish were potentially heavily targeted by the historical (pre-WWII) fishery. With the assessment for prickly redfish beginning in 1995, it is implicit that this species had recovered to unexploited levels by inception of the QSCF. This assumption was tested by including a scenario (scenario 20 in Table 2.3) for the harvest history for prickly redfish that included a potential significant depletion due to the early fishery, up until about 1940. The two curryfish species were essentially not acceptable to the fishery and so were not harvested until suitable handling and processing methods were developed for the species, in the mid-2000s. Beginning the assessment period from 1995 is thus acceptable for these species.

Using methods from the R package XSSS (Wetzel et al. 2015) the model was run with a start year of 1892 and depletion in 1940 at 60%. Figure F.28 demonstrates that there is a probable degree of recovery from heavily exploited to unexploited levels.

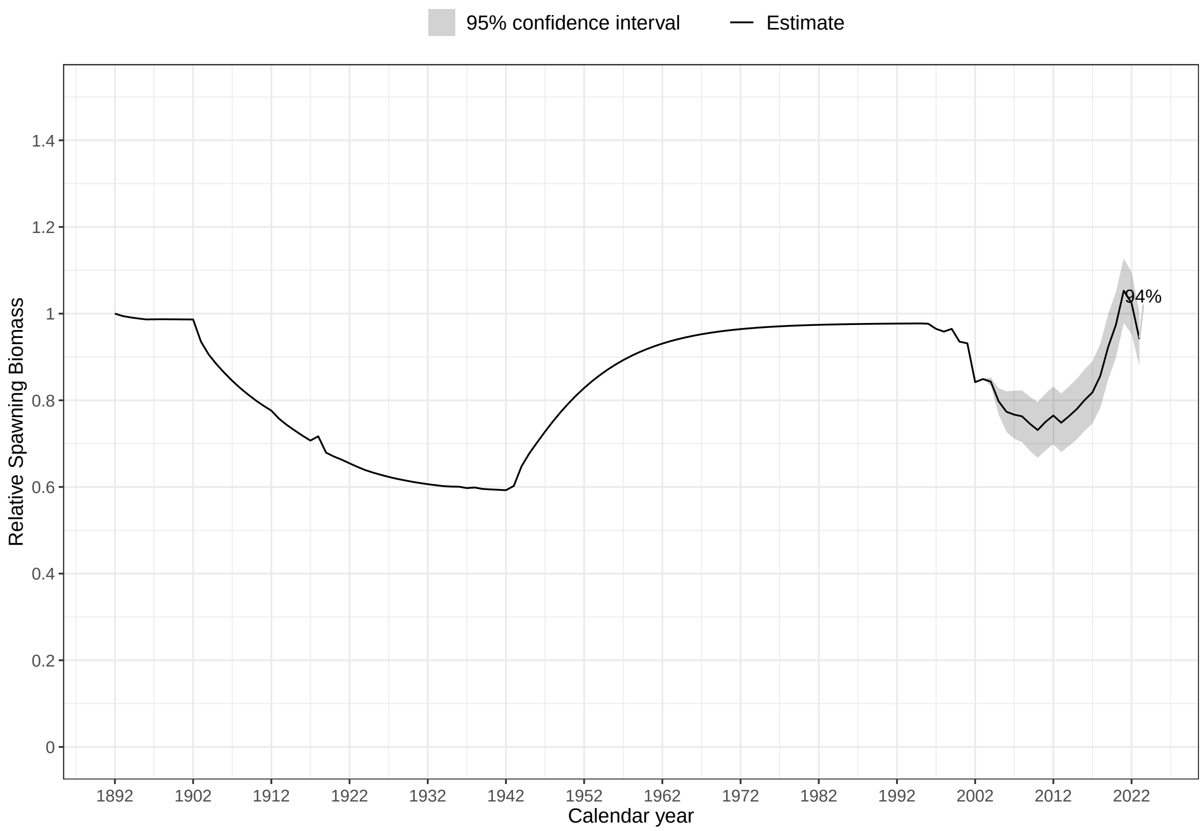


Figure F.28: MLE estimated biomass trajectory relative to unfished for scenario 20 Stock Synthesis model for prickly redfish, from 1982 to 2023.

Appendix G DDUST Scenario outputs

Table G.1: Scenarios tested to determine sensitivity to parameters, assumptions and model inputs for DDUST. Scenario numbers match those of the Stock Synthesis Scenarios when applicable.

Scenario	Species	Description
1	All	Base case
2	All	Low steepness (*h*)
3	All	High steepness (*h*)
4	All	Low recruitment variability (σ_R)
5	All	High recruitment variability (σ_R)
6	All	Low natural mortality (*M*)
7	All	High natural mortality (*M*)
8	All	Extra catch rate variance
9	All	No survey scaling
10	All	Low survey scaling
11	All	High survey scaling
15	H. curryfish and v. curryfish	Reported logbook catch
21	All	Slower growth
22	All	Faster growth

G.1 Sensitivity

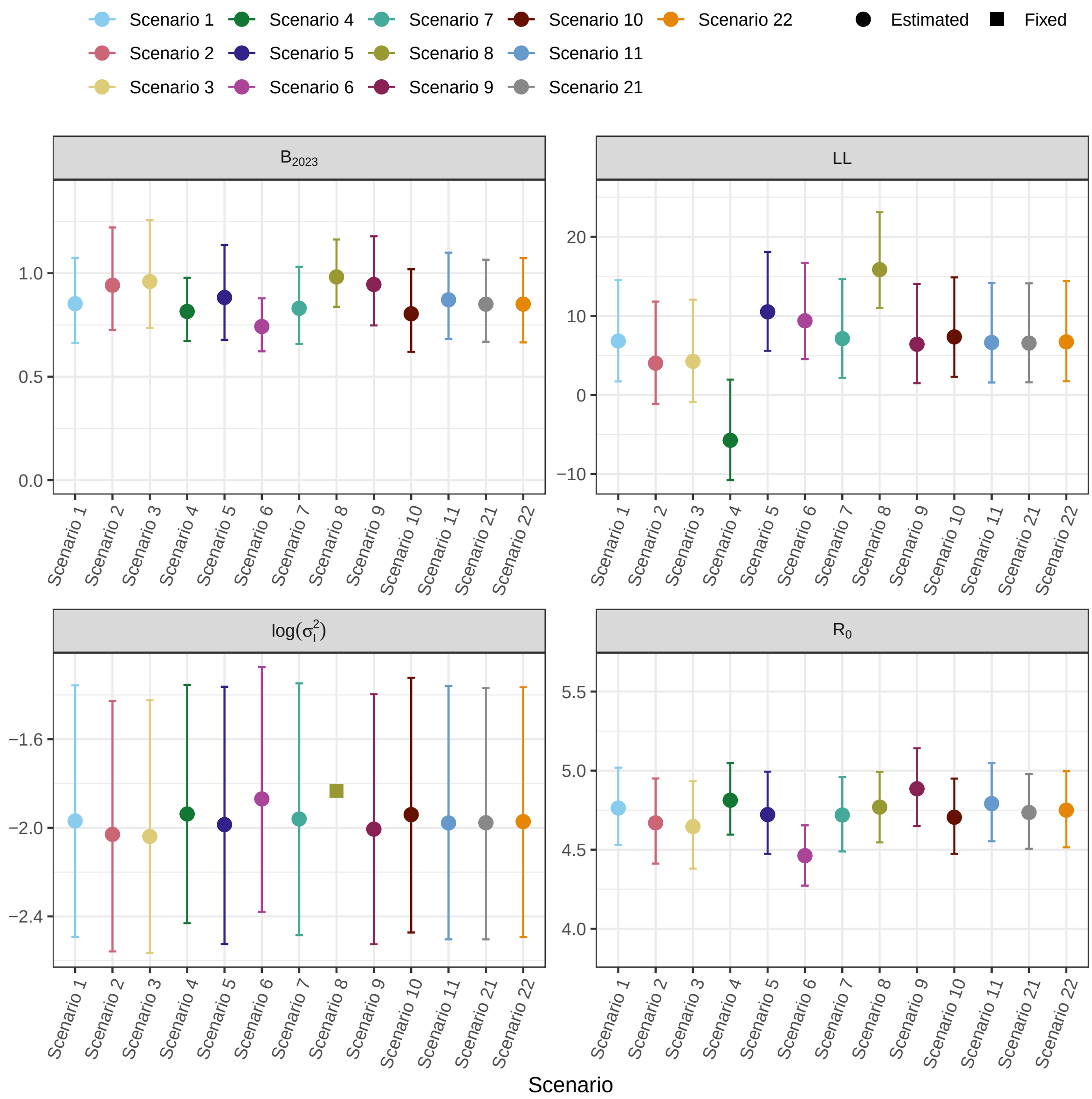


Figure G.1: DDUST sensitivity plots of estimated parameters for prickly redfish.

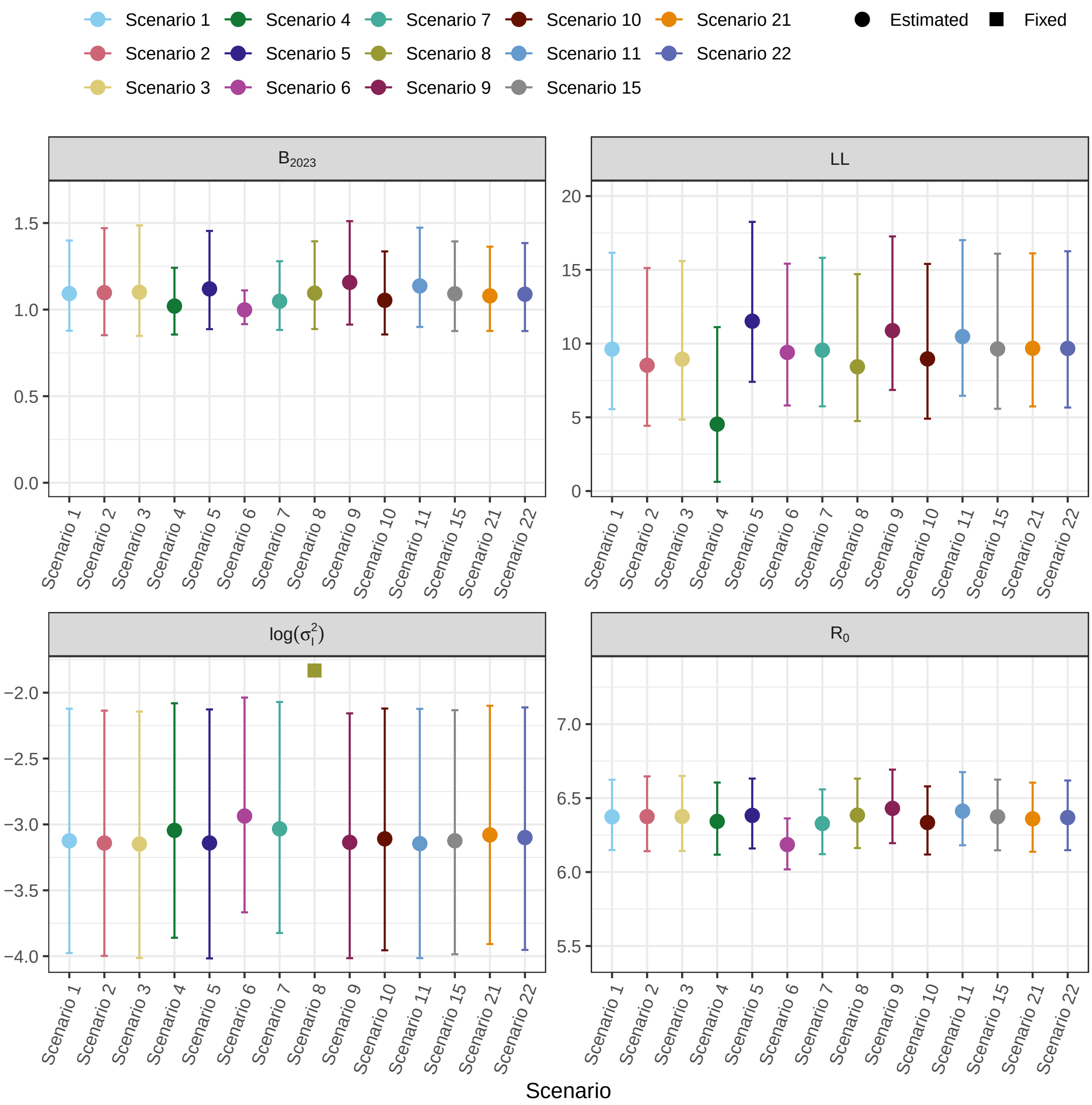


Figure G.2: DDUST sensitivity plots of estimated parameters for herrmanni curryfish.

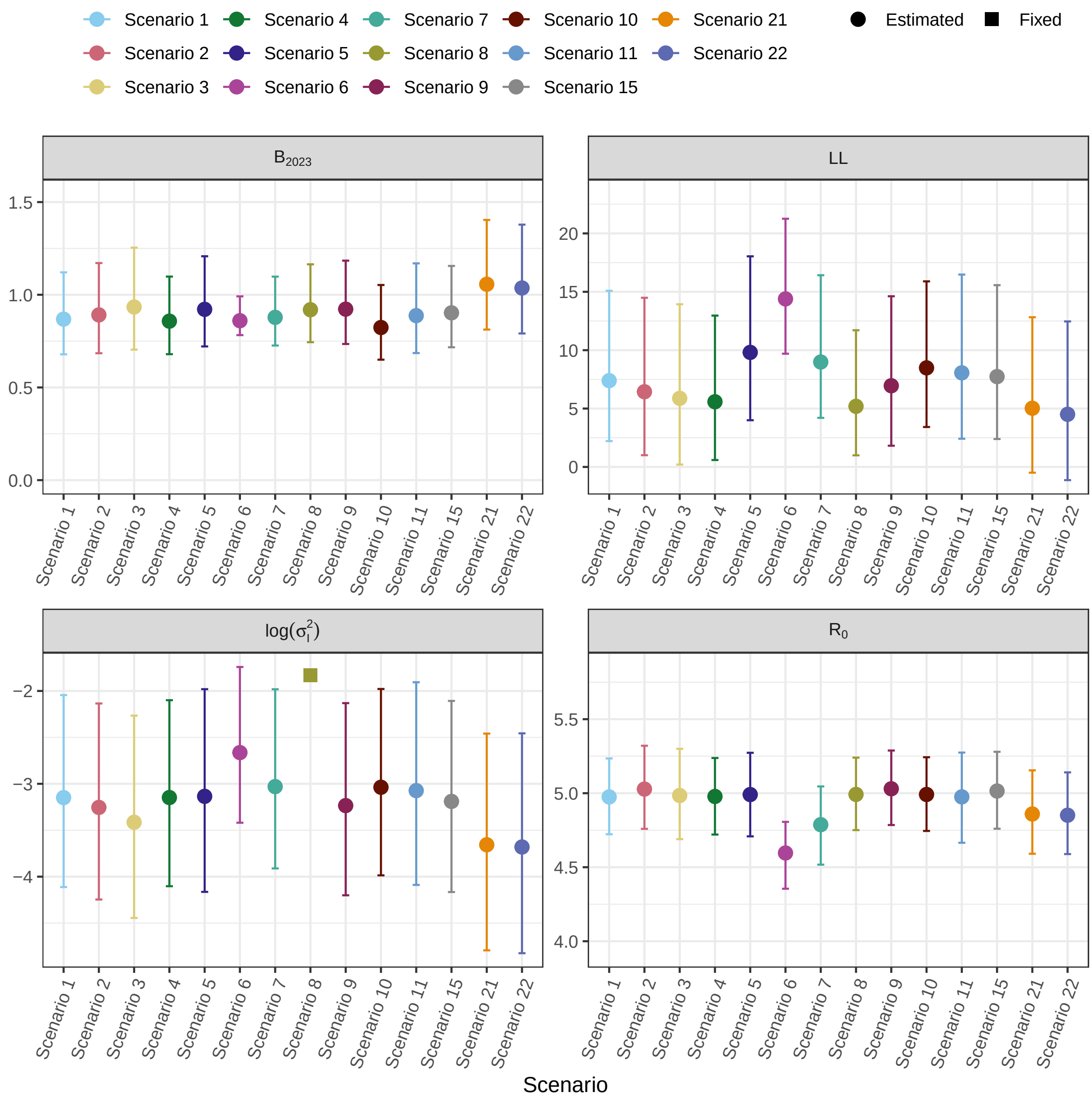


Figure G.3: DDUST sensitivity plots of estimated parameters for vastus curryfish.

G.2 Biomass

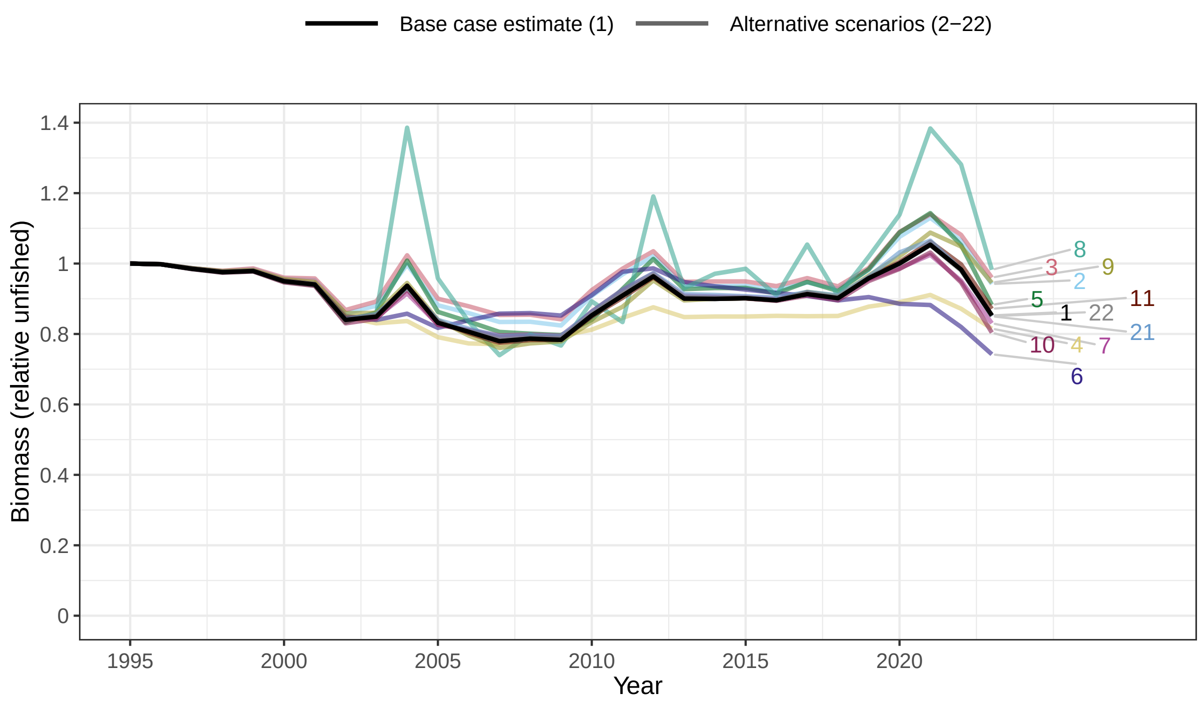


Figure G.4: MCMC predicted biomass trajectory relative to unfished for prickly redfish, from 1995 to 2023 for all DDUST model scenarios.

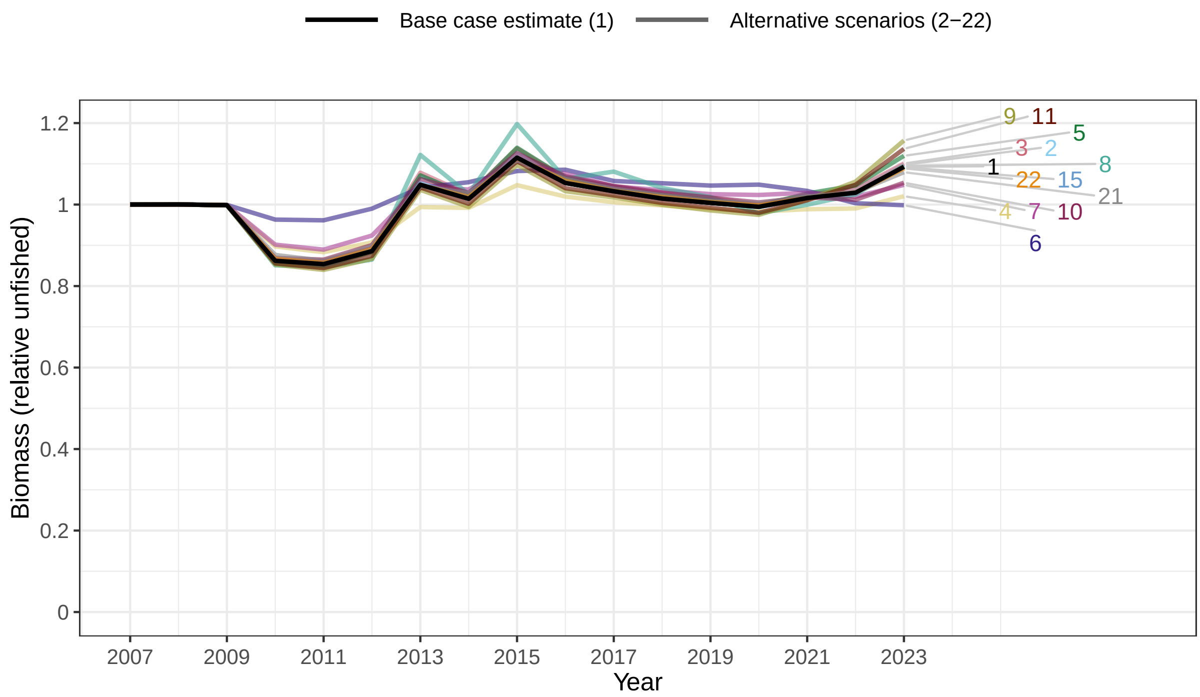


Figure G.5: MCMC predicted biomass trajectory relative to unfished for herrmanni curryfish, from 2007 to 2023 for all DDUST model scenarios.

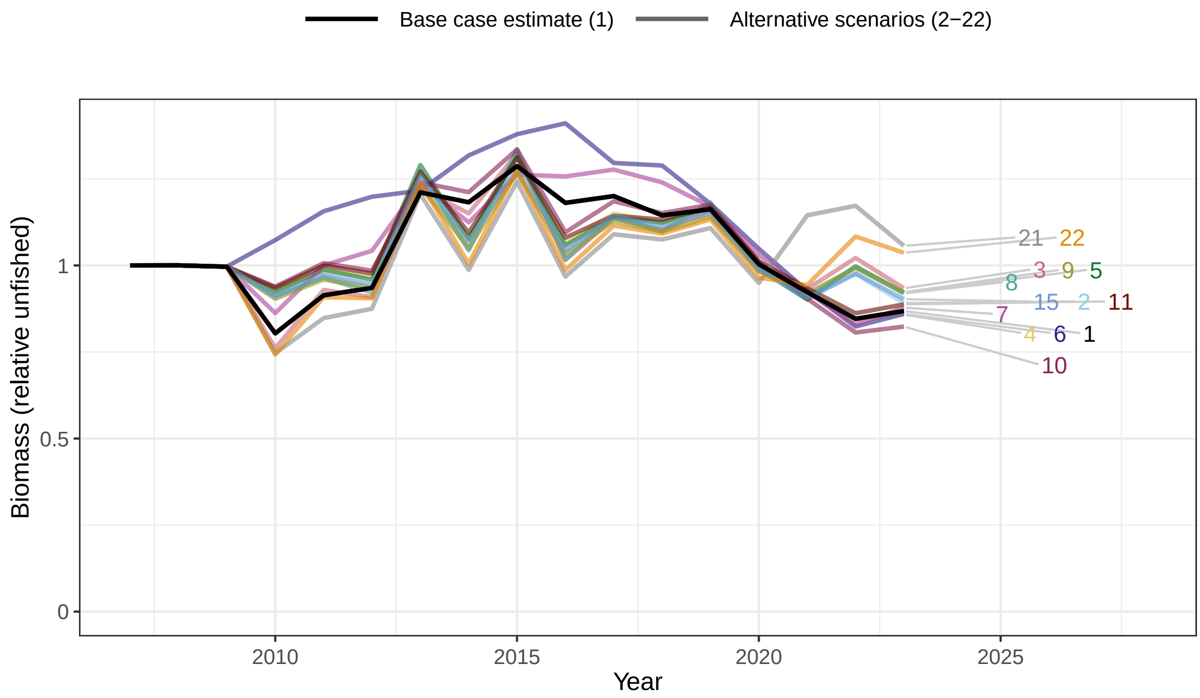


Figure G.6: MCMC predicted biomass trajectory relative to unfished for vastus curryfish, from 2007 to 2023 for all DDUST model scenarios.

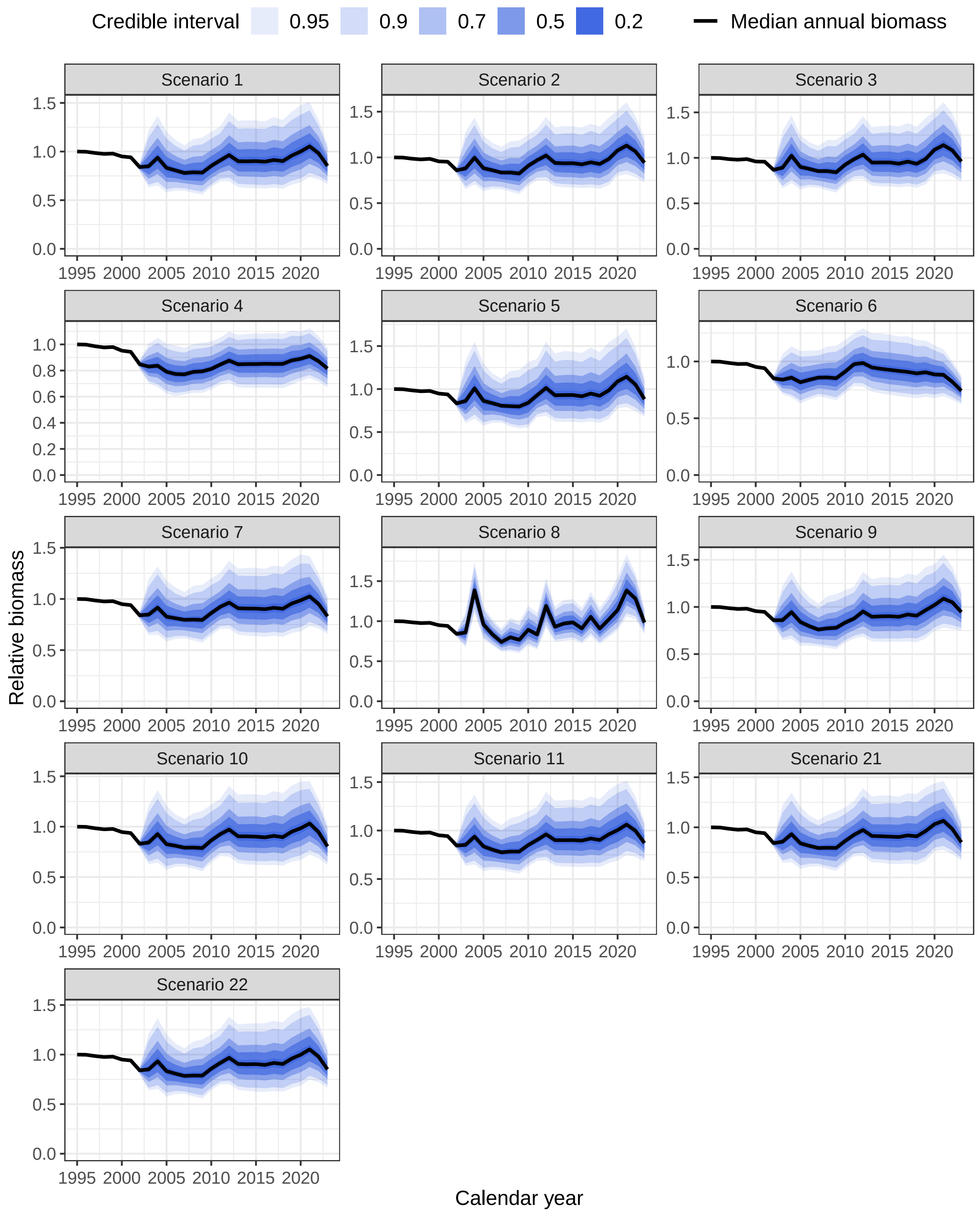


Figure G.7: MCMC predicted biomass trajectory relative to unfished from the DDUST model sensitivity scenarios for prickly redfish, from 1995 to 2023.

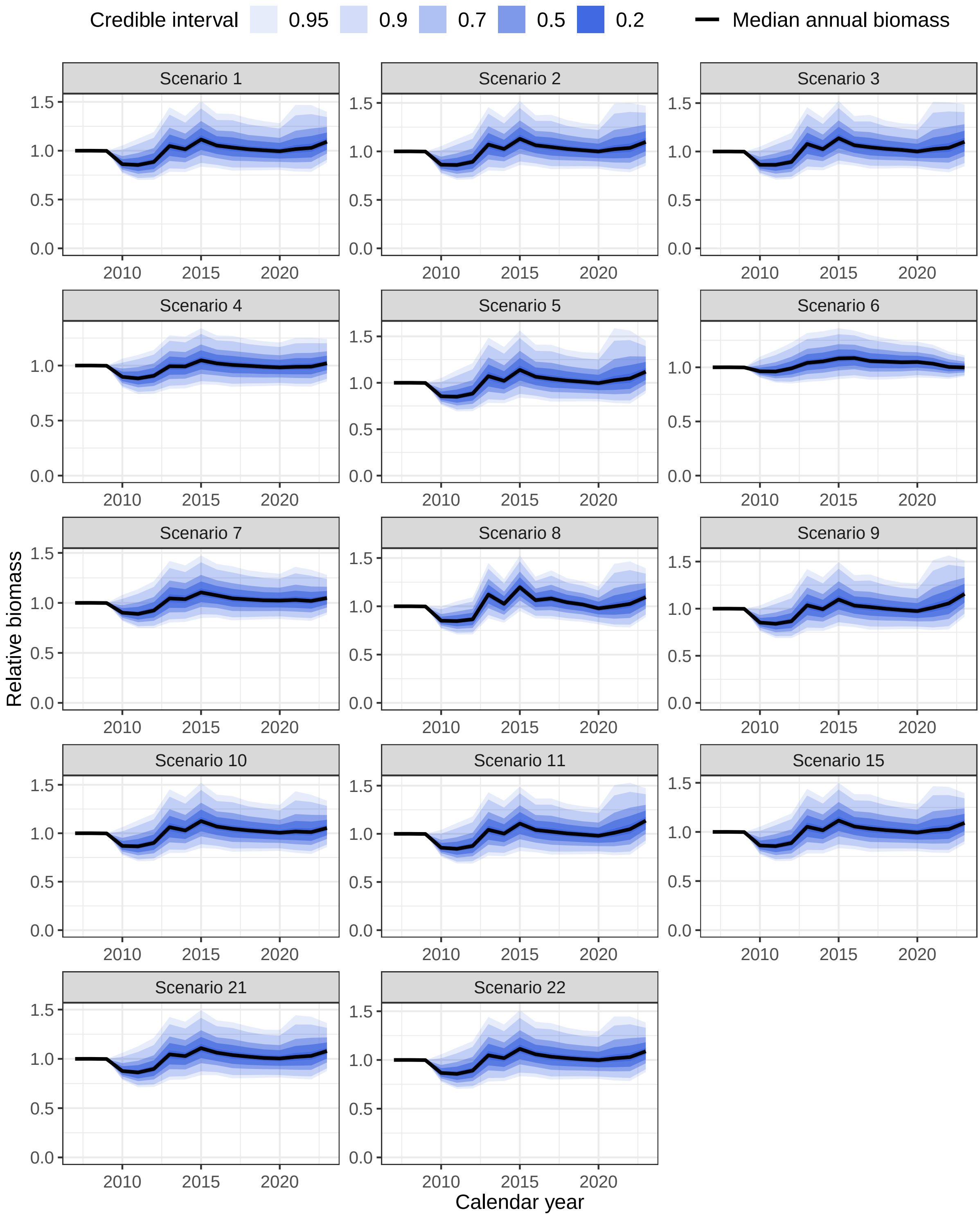


Figure G.8: MCMC predicted biomass trajectory relative to unfished from the DDUST model sensitivity scenarios for herrmanni curryfish, from 2007 to 2023.

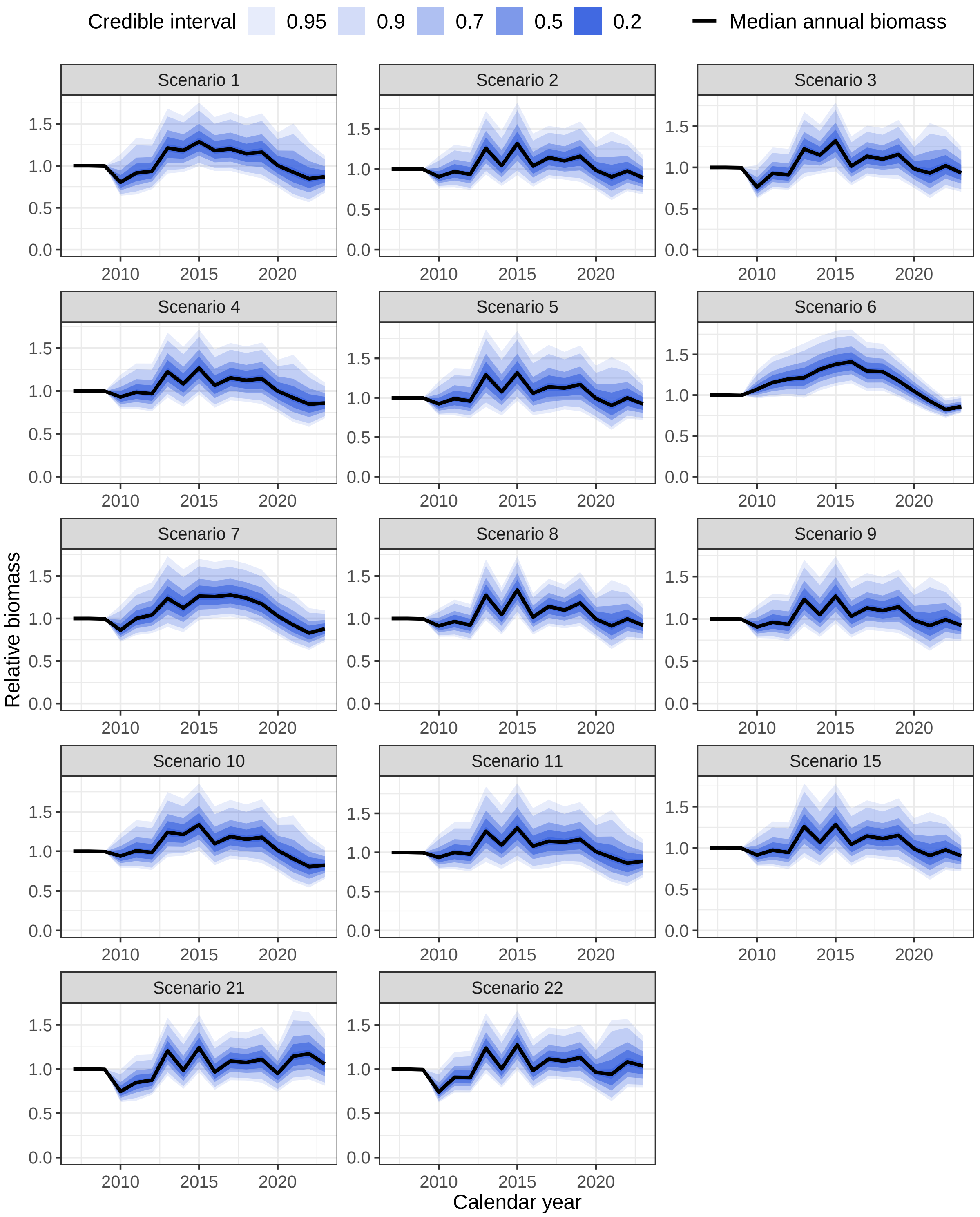


Figure G.9: MCMC predicted biomass trajectory relative to unfished from the DDUST model sensitivity scenarios for vastus curryfish, from 2007 to 2023.

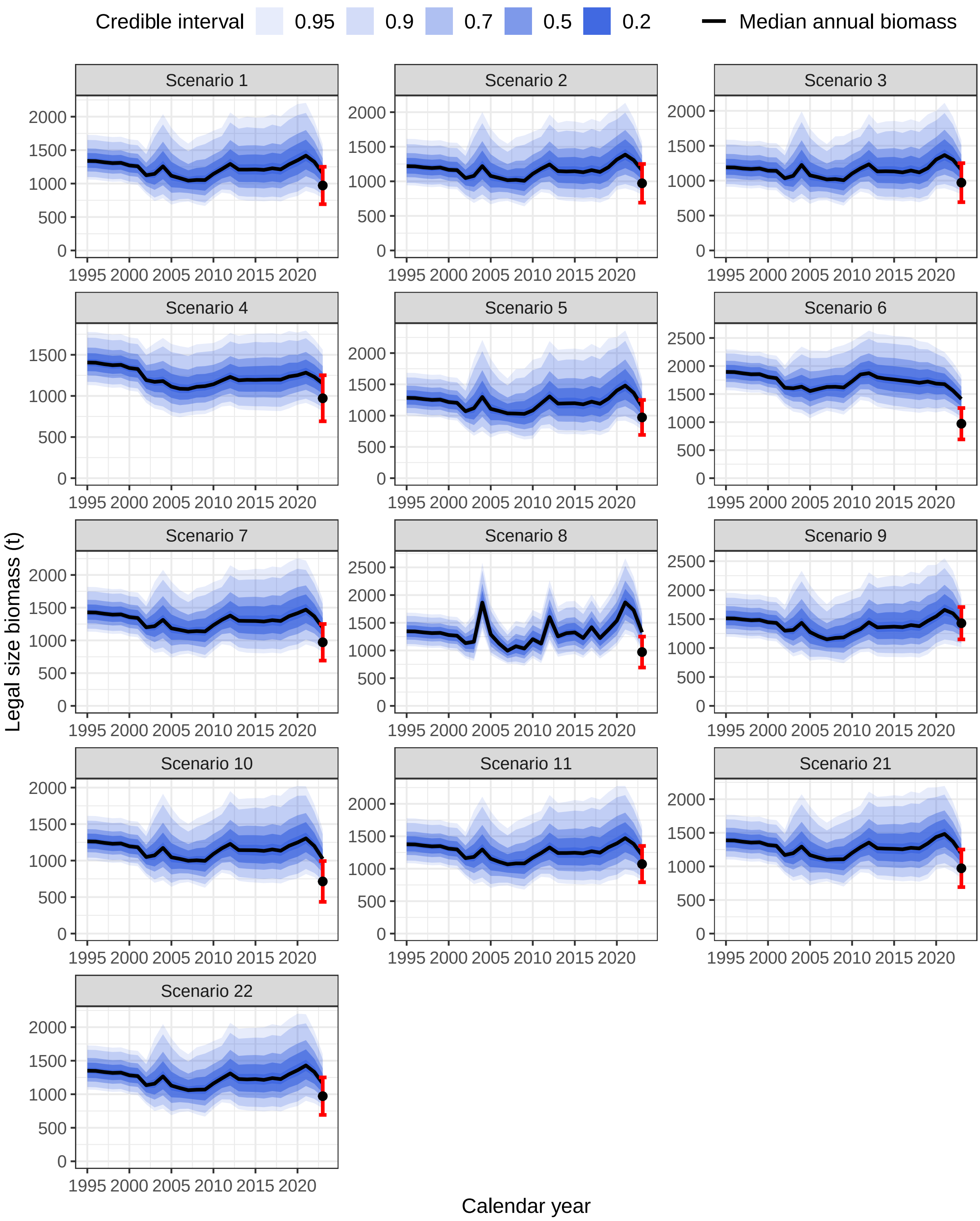


Figure G.10: Model fits to legal-sized biomass (black point with red error bars indicating the sd of the estimate) for prickly redfish, from 1995 to 2023 for each DDUST sensitivity scenario.

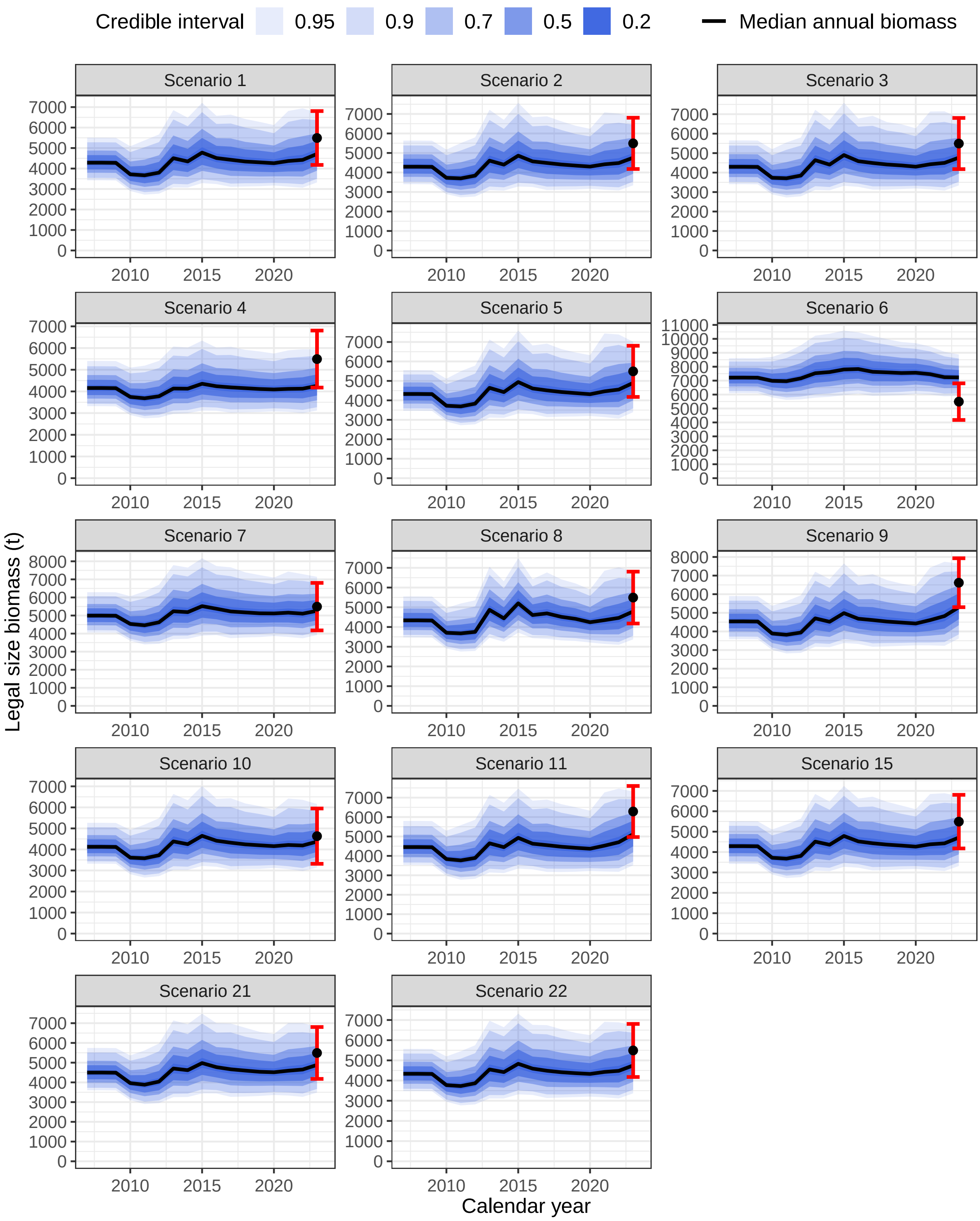


Figure G.11: Model fits to legal-sized biomass (black point with red error bars indicating the sd of the estimate) for herrmanni curryfish, from 2007 to 2023 for each DDUST sensitivity scenario.

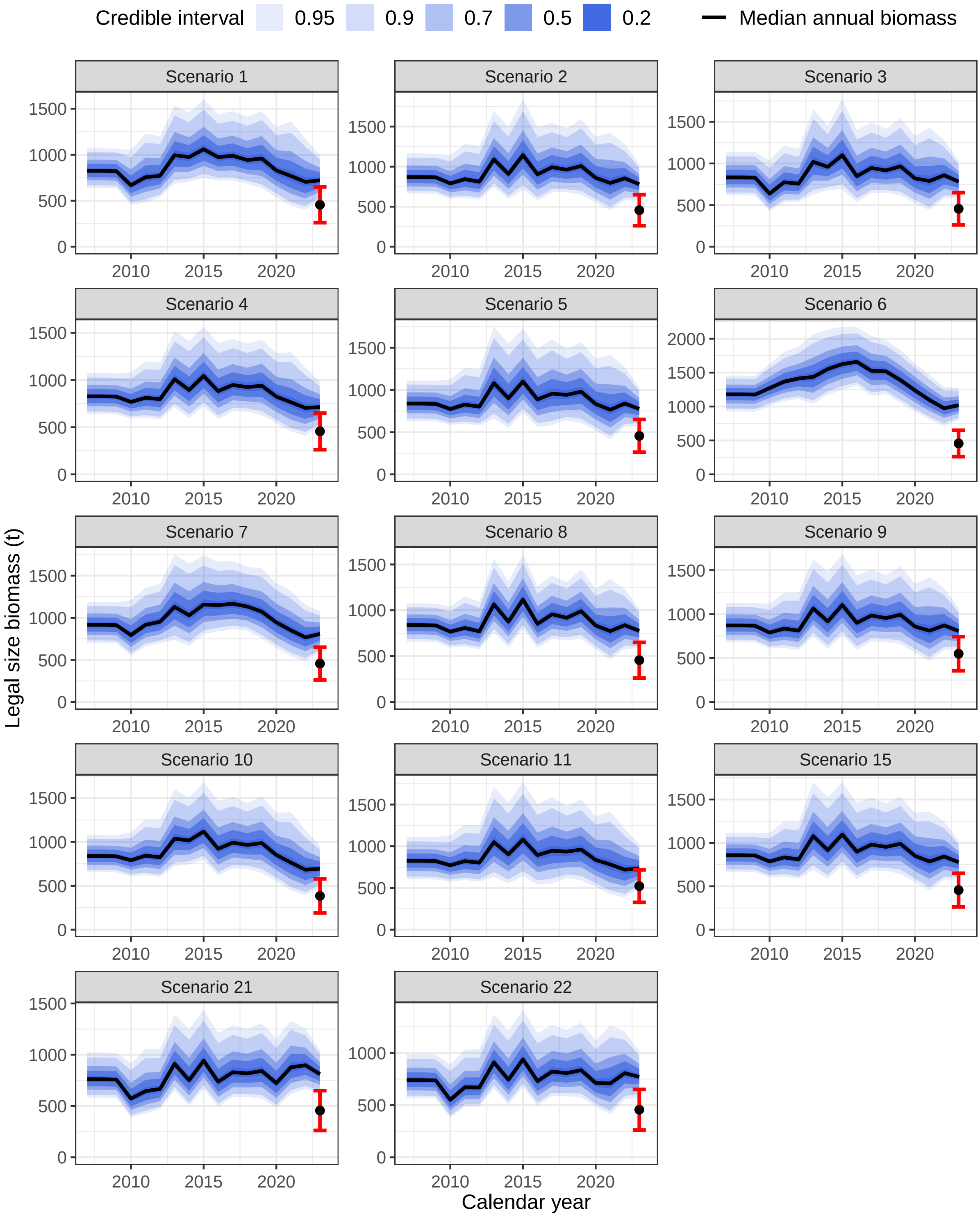


Figure G.12: Model fits to legal-sized biomass (black point with red error bars indicating the sd of the estimate) for vastus curryfish, from 2007 to 2023 for each DDUST sensitivity scenario.

G.3 Abundance indices

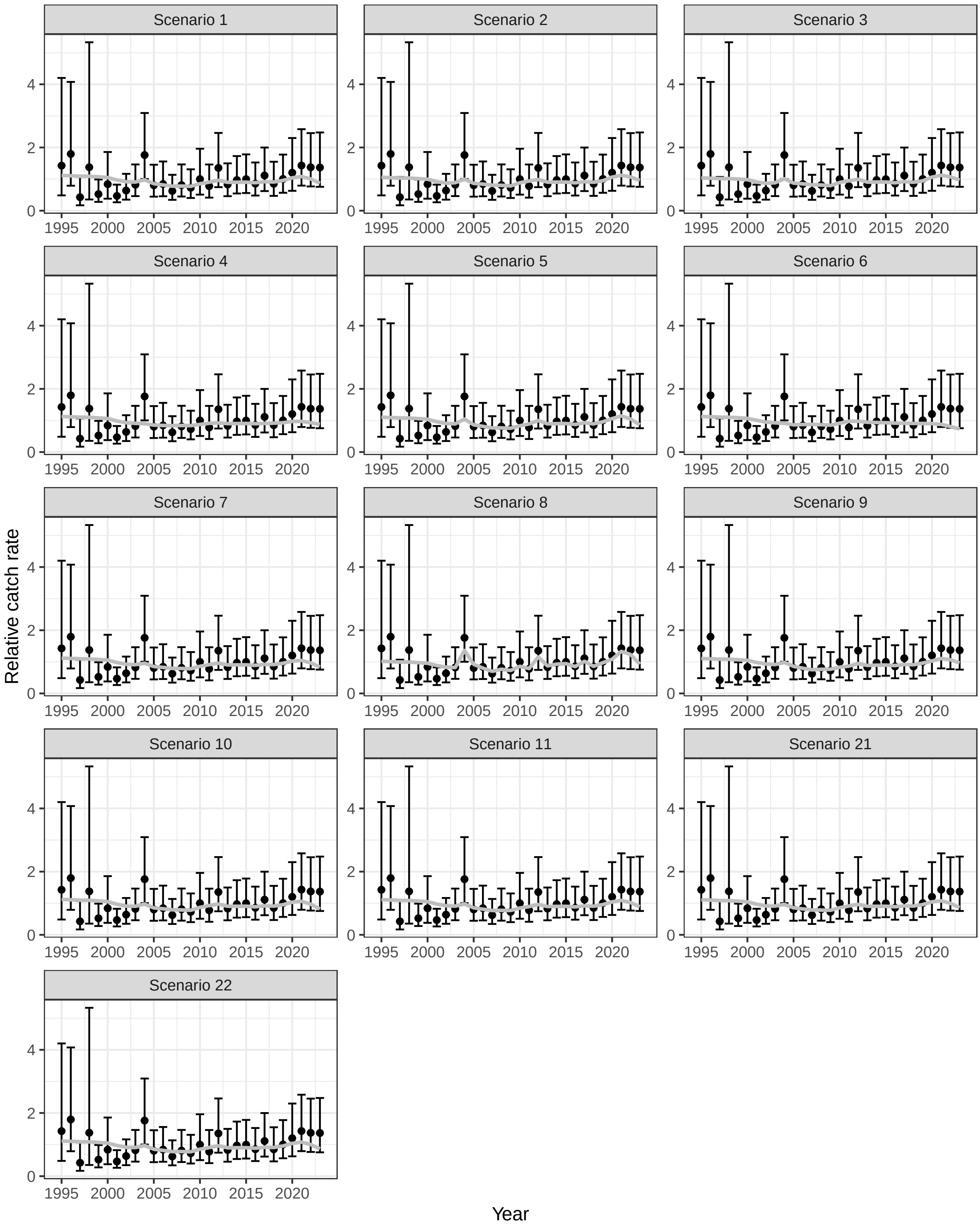


Figure G.13: Model predictions to commercial catch rates for prickly redfish, from 1995 to 2023 for each DDUST sensitivity scenario.

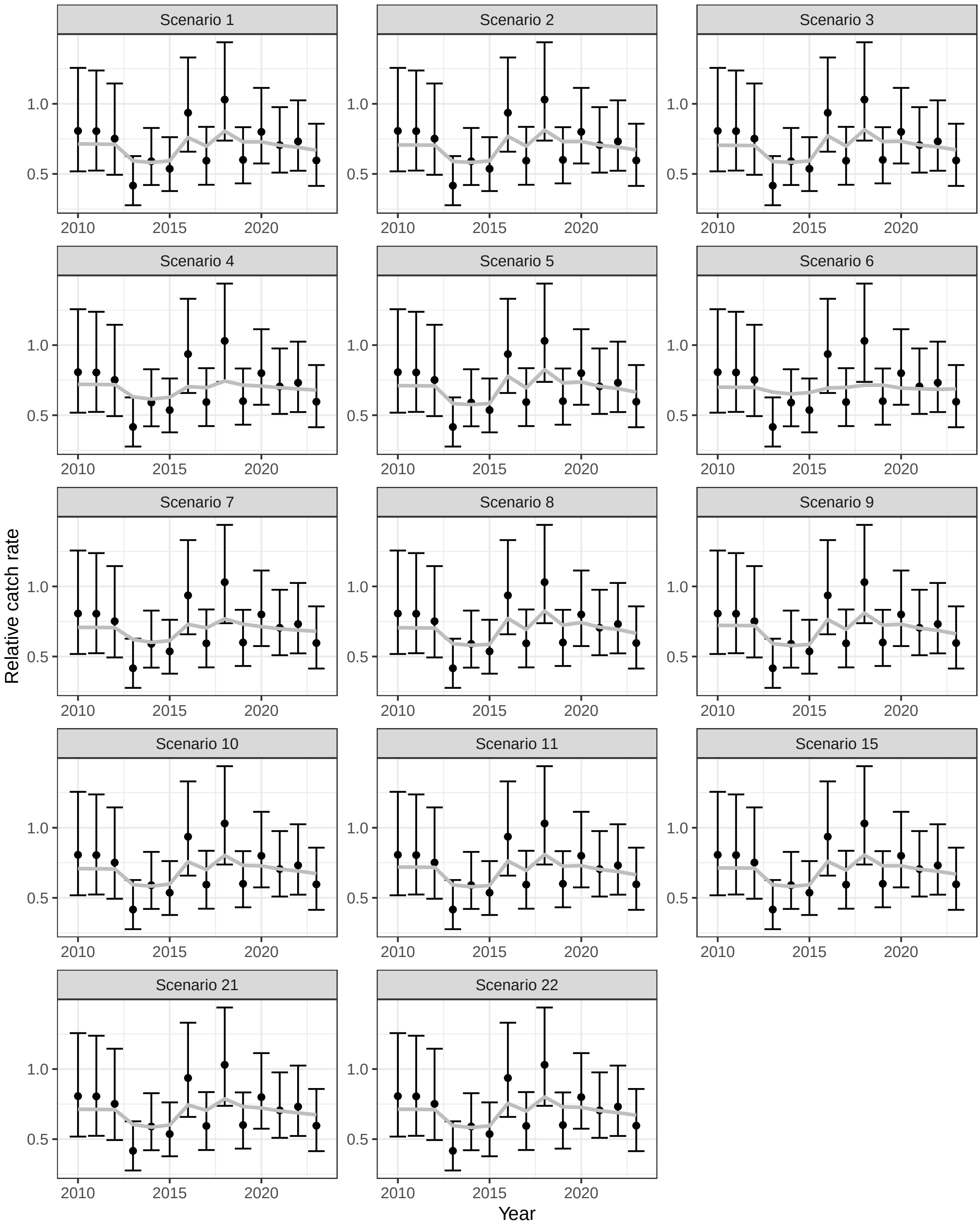


Figure G.14: Model predictions to commercial catch rates for herrmanni curryfish, from 2010 to 2023 for each DDUST sensitivity scenario.

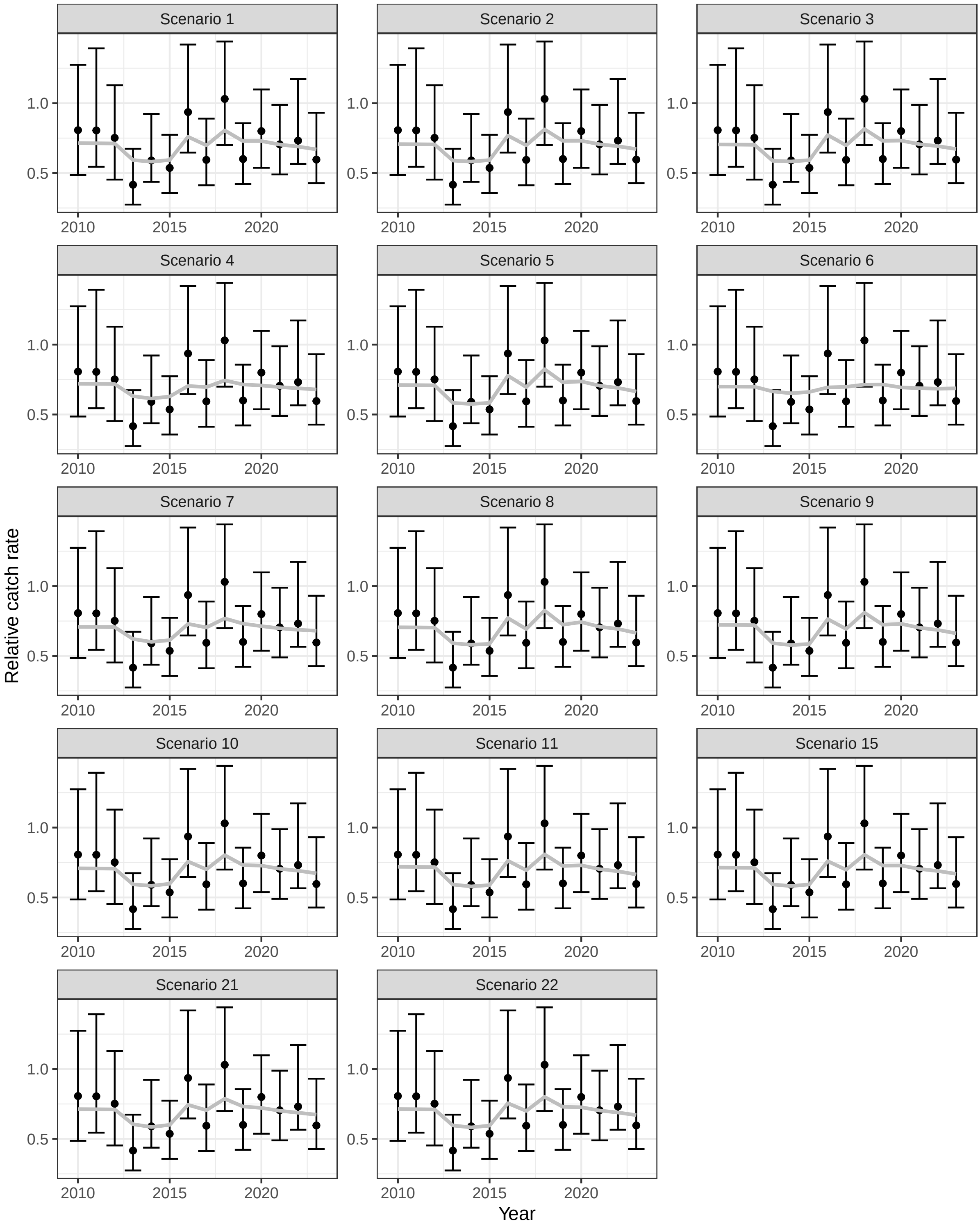


Figure G.15: Model predictions to commercial catch rates for vastus curryfish, from 2010 to 2023 for each DDUST sensitivity scenario.

G.4 Stock recruitment

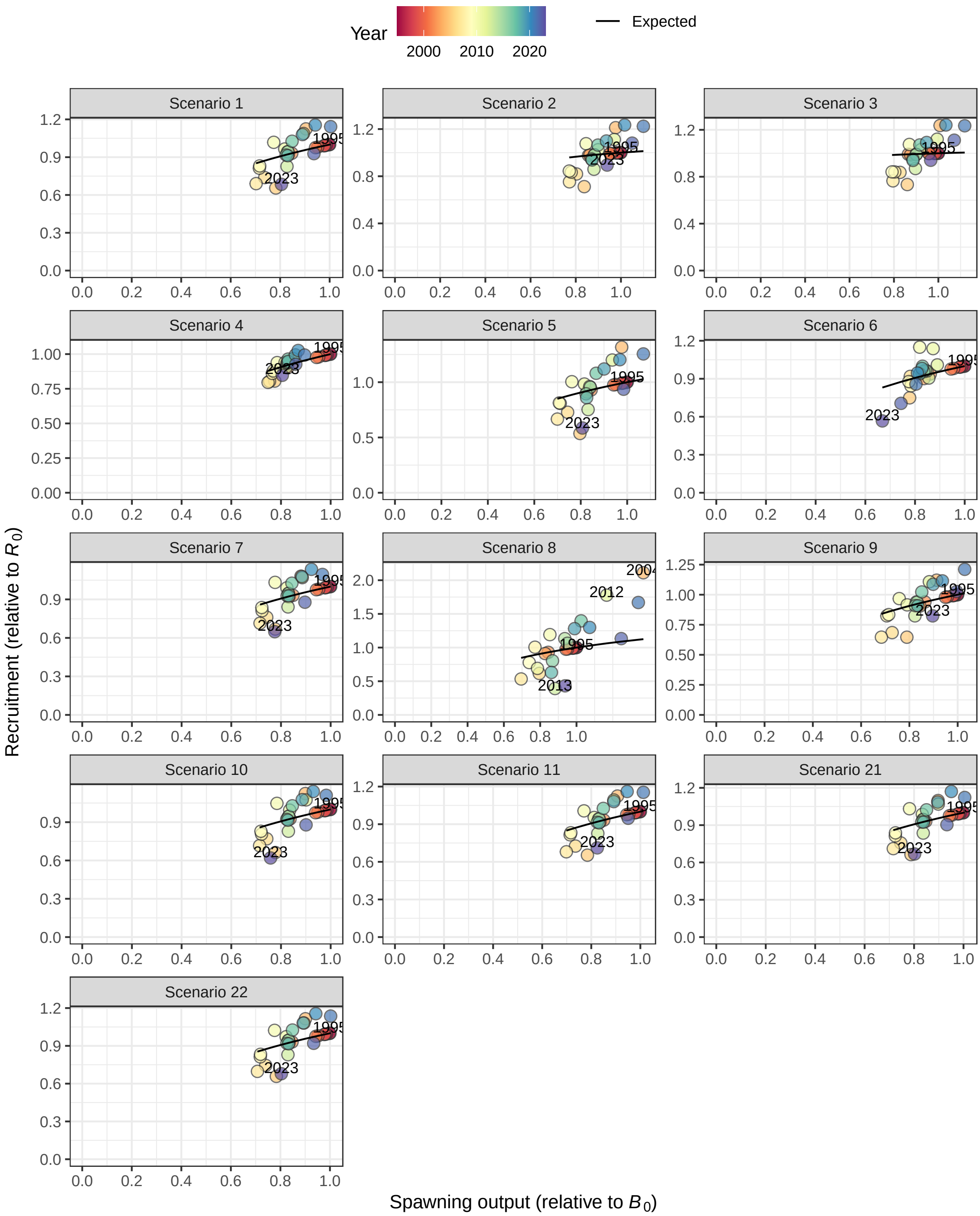


Figure G.16: Stock-recruitment curve for all sensitivity scenarios conducted for prickly redfish DDUST model. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

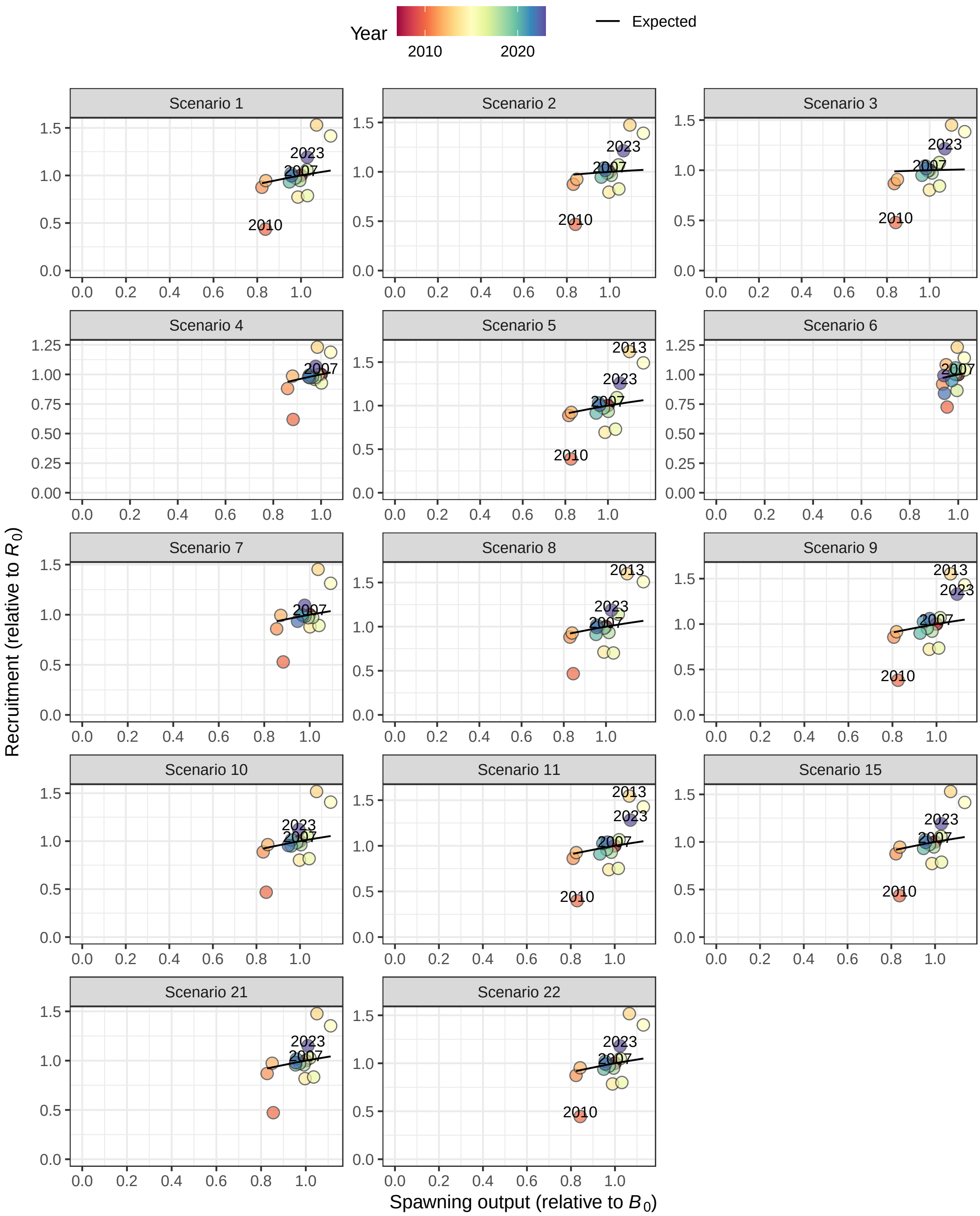


Figure G.17: Stock-recruitment curve for all sensitivity scenarios conducted for herrmanni curryfish DDUST model. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

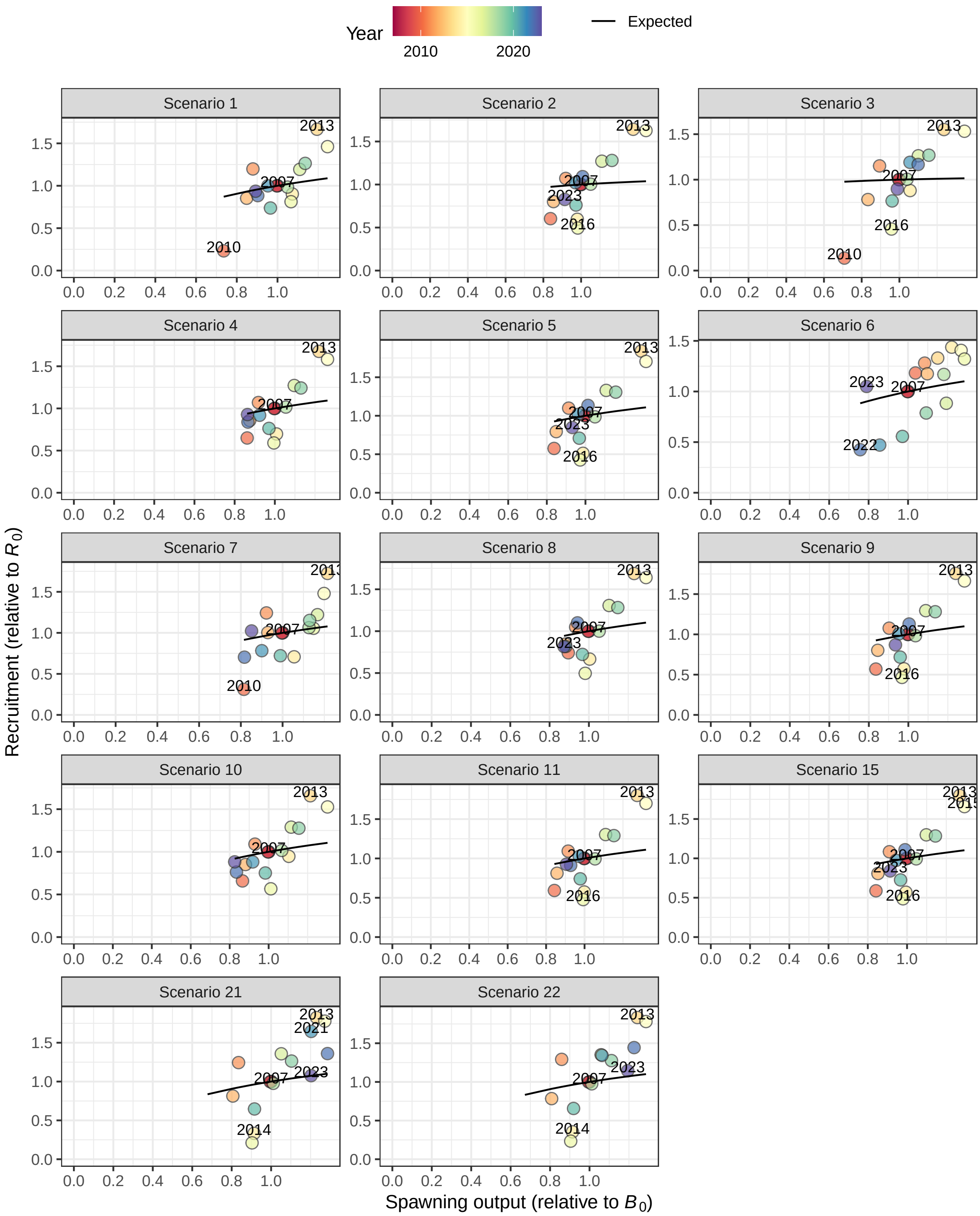


Figure G.18: Stock-recruitment curve for all sensitivity scenarios conducted for vastus curryfish DDUST model. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

G.5 Recruitment deviations

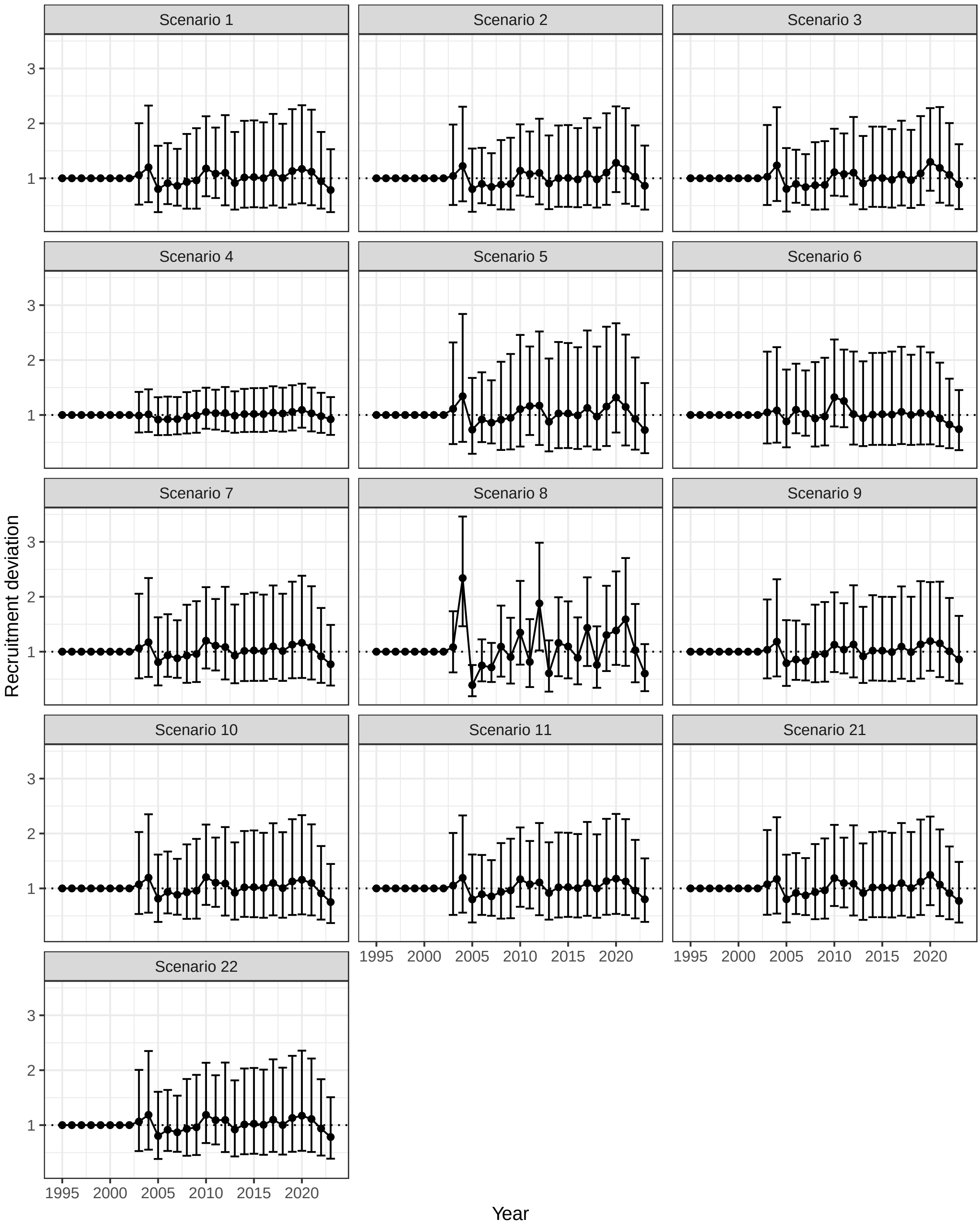


Figure G.19: Recruitment deviations for all sensitivity scenarios conducted for the prickly redfish DDUST model, from 2003 to 2023.

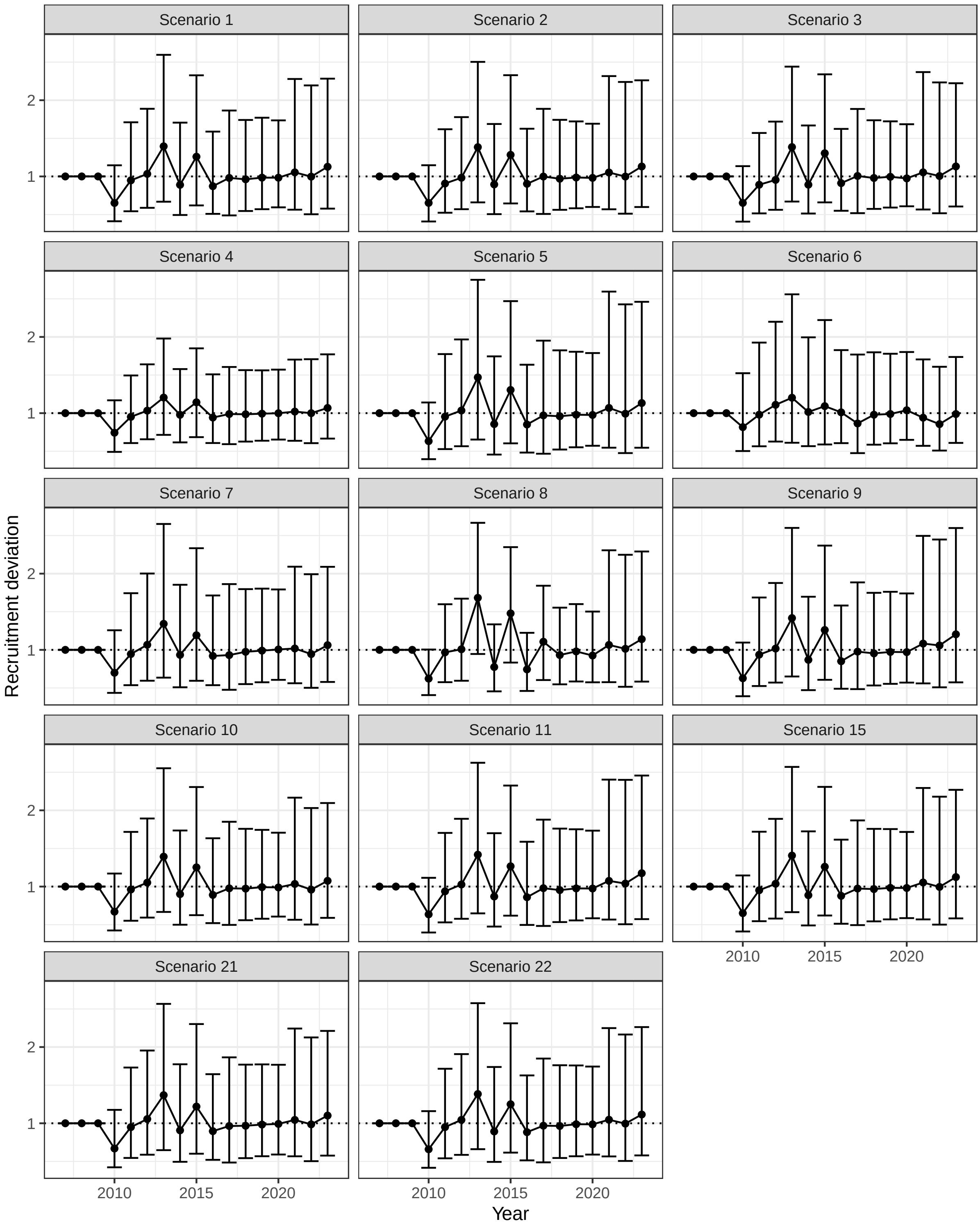


Figure G.20: Recruitment deviations for all sensitivity scenarios conducted for herrmanni curryfish DDUST model, from 2010 to 2023.

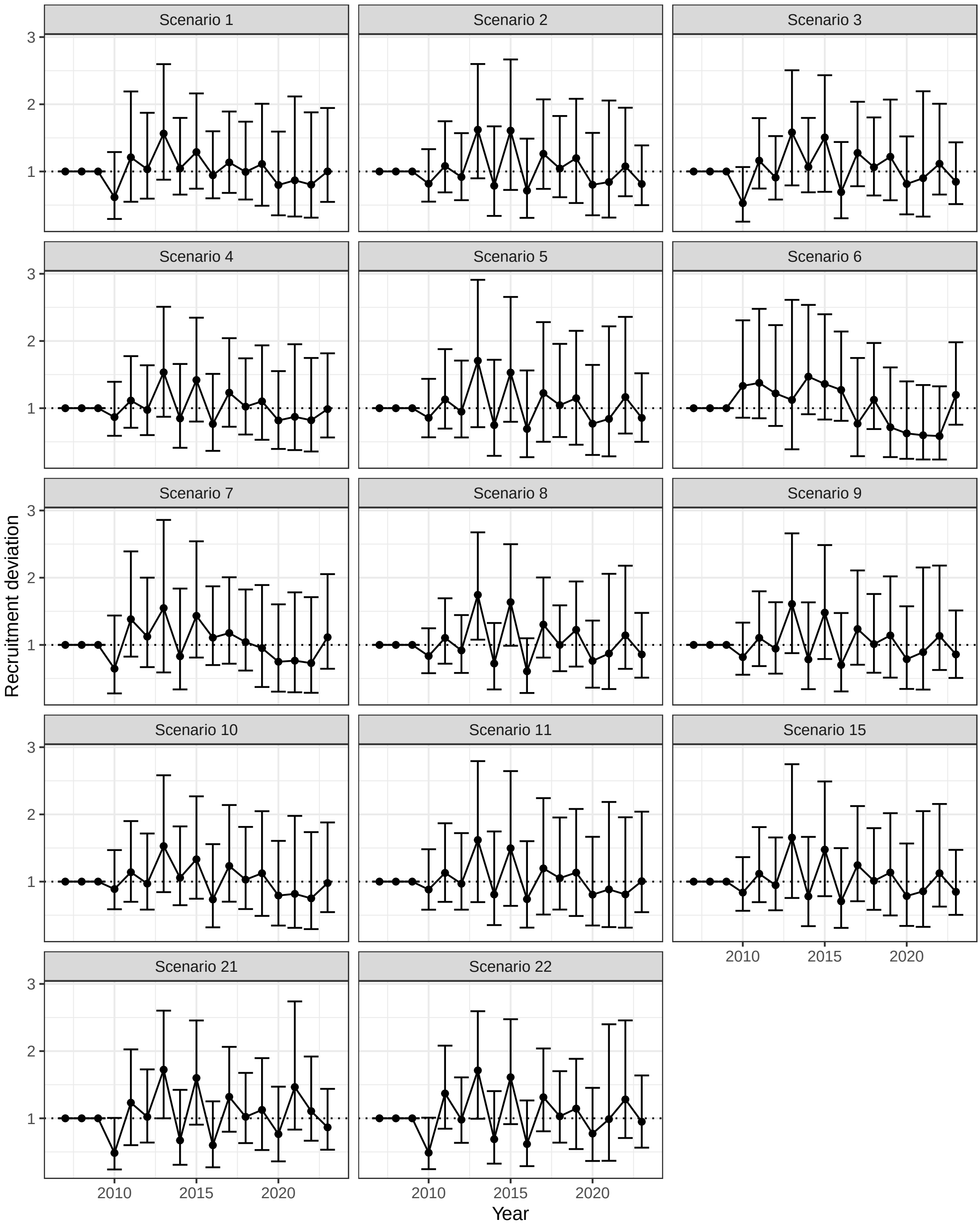


Figure G.21: Recruitment deviations for all sensitivity scenarios conducted for vastus curryfish DDUST model, from 2010 to 2023.

G.6 Fishing mortality

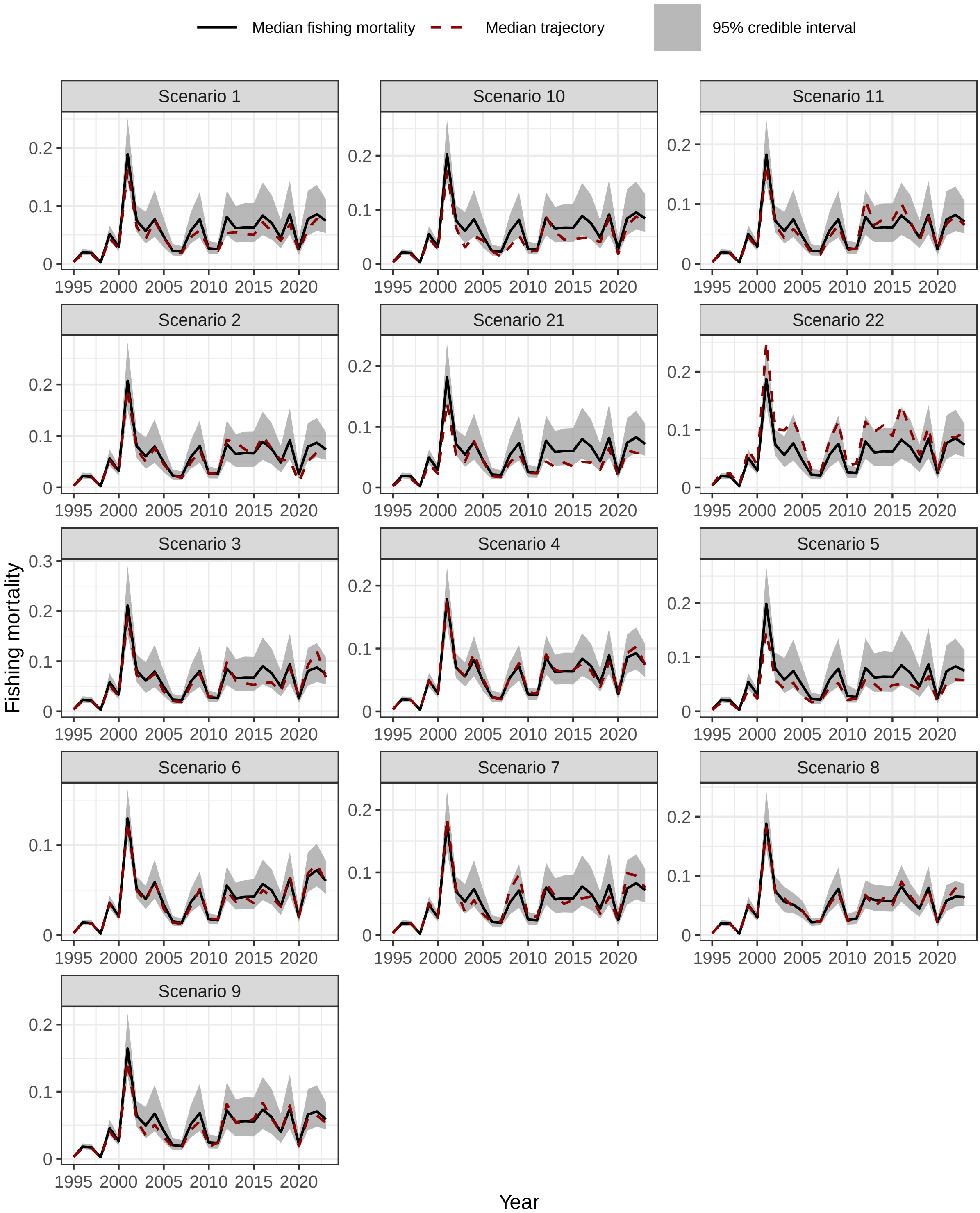


Figure G.22: Predicted fishing mortality (F) for all sensitivity scenarios conducted for the prickly redfish DDUST model, from 1995 to 2023.

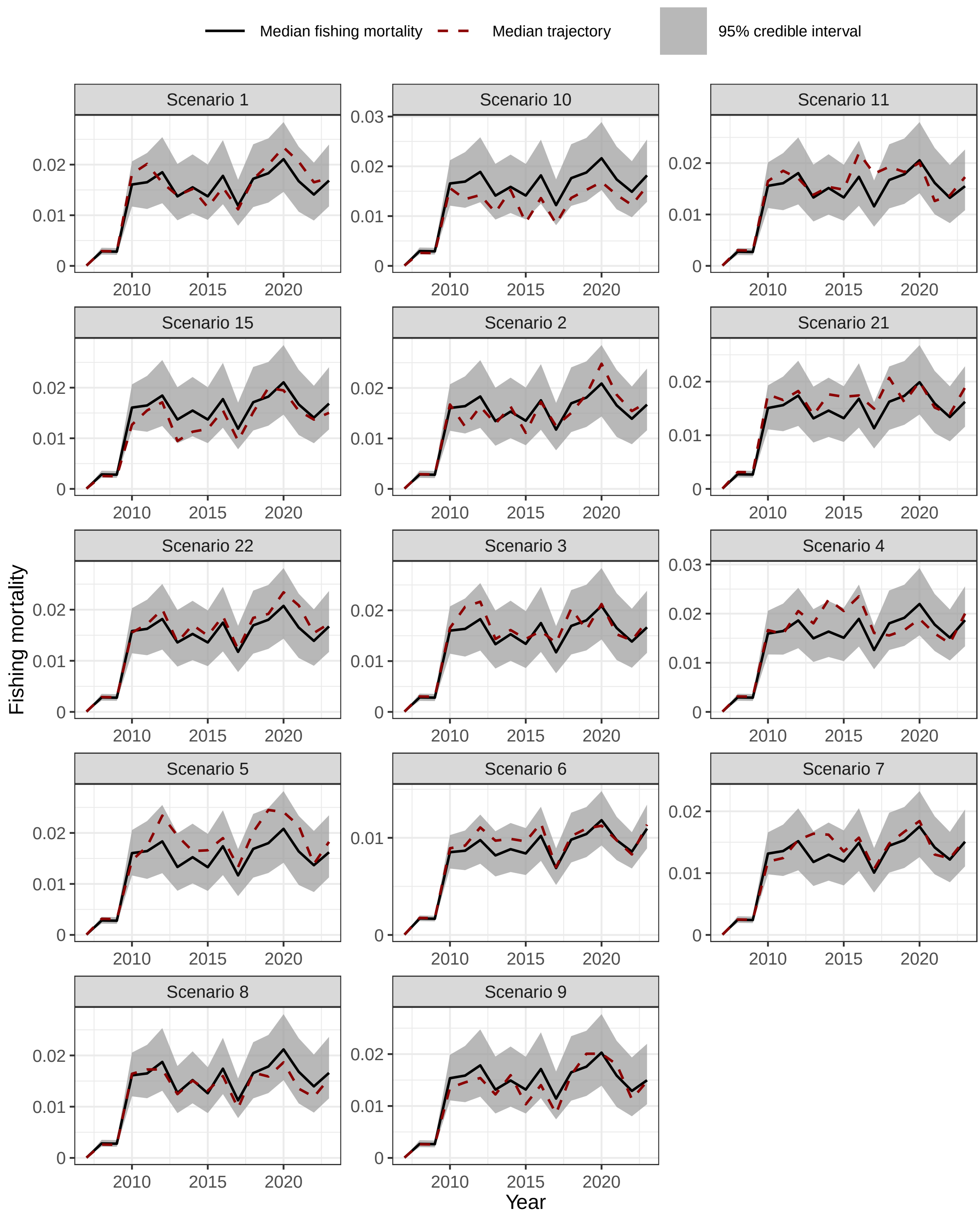


Figure G.23: Predicted fishing mortality (F) for all sensitivity scenarios conducted for the hermanni curryfish DDUST model, from 2007 to 2023.

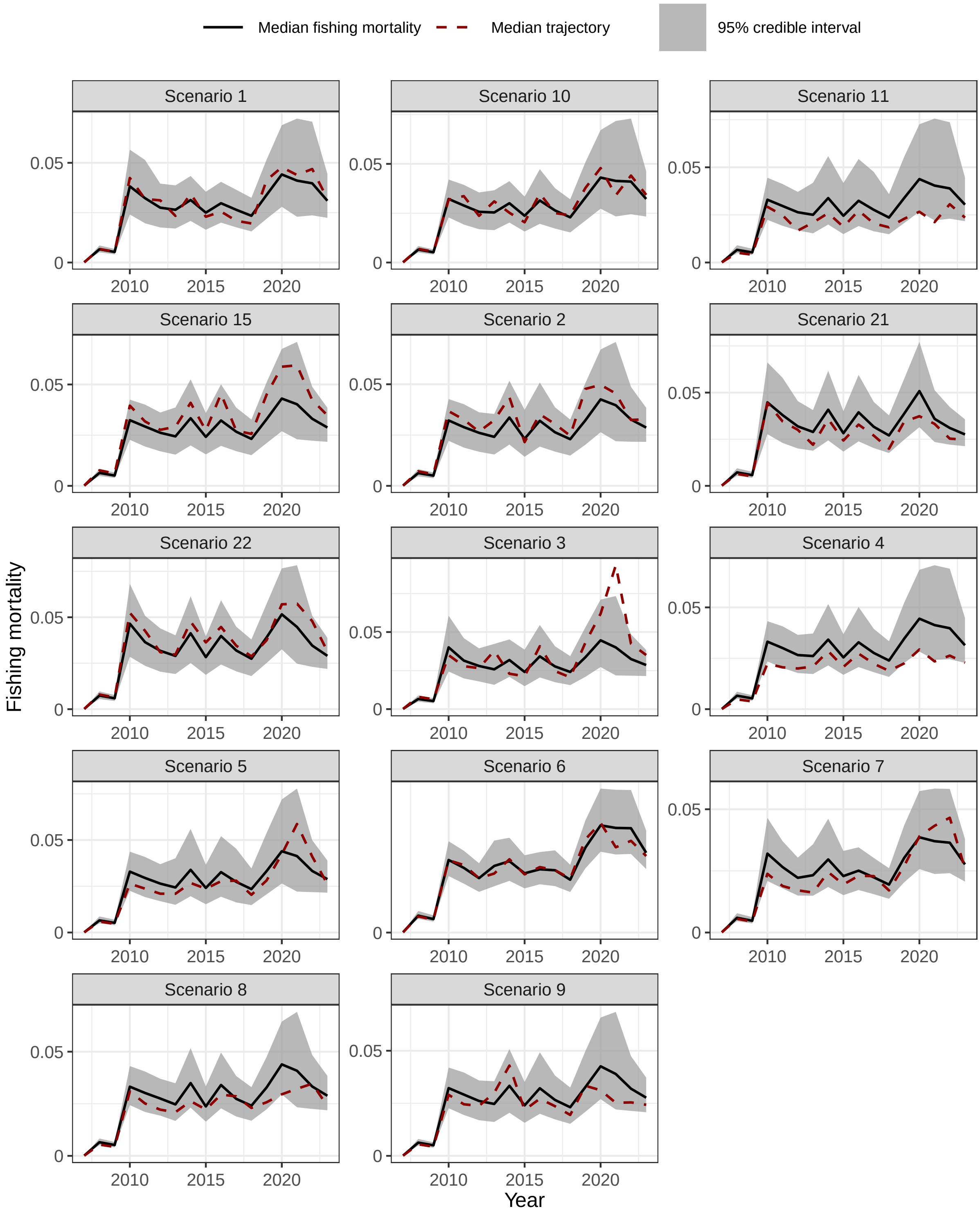


Figure G.24: Predicted fishing mortality (F) for all sensitivity scenarios conducted for the vastus curryfish DDUST model, from 2007 to 2023.

Appendix H 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. (2006), Courtney et al. (2014), O'Neill et al. (2014), and Helidoniotis (2021). Functionality has been introduced to allow the user to specify the time step used for delays and incorporate seasonal variation in recruitment, spawning, and catchability. The delay-difference with user specified time step (DDUST) model allows for monthly, bimonthly, trimonthly, quadmonthly, semi-annual and annual biomass dynamics.

H.1 Mathematical formulation

H.1.1 Population dynamics

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

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

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

The spawning biomass at time t depends on the spawning biomass in the two previous time steps. The growth of the population is controlled through the parameter ρ and the total mortality (natural and fishing) is represented by s. The first term in equation (H.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 simpler to track but often less important. Without the need to track growth or weight, equation (H.2) describes individuals experiencing mortality and the addition of recruits. A key feature of the DDUST 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.

H.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,

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

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 (H.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 can optionally be treated as fixed effects or random effects by integrating the recruitment parameters out of the likelihood. If the recruitment deviations are random effects, the relationship between the annual recruitment R_t and the deviated recruitment R_t^* is as follows,

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

The subtraction of $\sigma_R^2/2$ ensures the mean of R_t^* is equal to the mean of R_t. 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,

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

A plot of the time series of recruitment deviations can reveal patterns or unusually high or low recruitment spikes which may prompt external reasoning. 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 (H.1) and (H.2) are updated using the recruitment deviations described in equation (H.4)

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

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

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

H.1.3 Spawning

The recruitment derived in equation (H.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

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

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

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

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

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

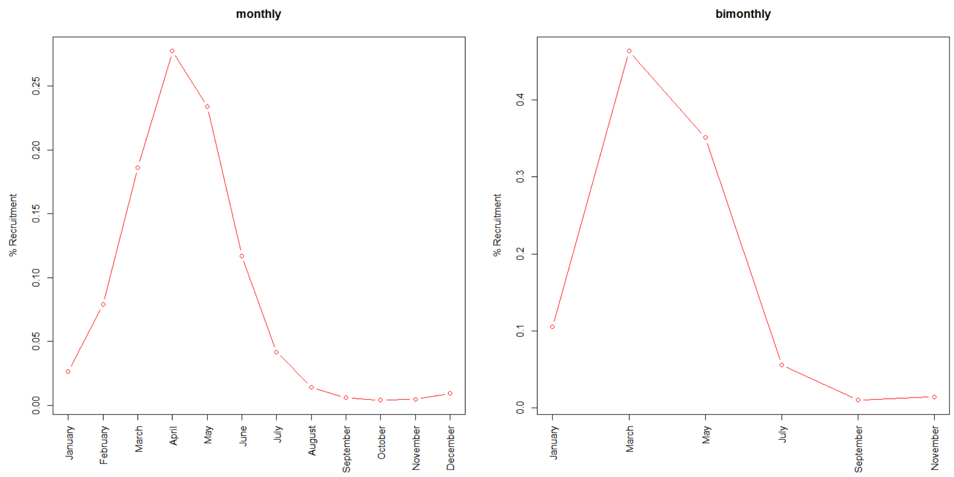


Figure H.1: Aggregation of a monthly recruitment pattern for a bi-monthly model

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

H.1.4 Seasonal patterns

The DDUST 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 according to the von Mises distribution and is governed by two parameters κ and μ which can be fixed or estimated by the model. The monthly recruitment pattern is described as

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

Due to the cyclic nature of the cosine function, the parameters κ and μ may produce the exact same pattern at different fixed values making unbounded estimation difficult. This can be overcome by bounding these parameters during optimisation. 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 bi-monthly 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 H.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.

H.1.5 Growth

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

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

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

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

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

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

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

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

Asymptotic weight from equation (H.16) is then

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

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:

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

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

H.1.6 Stock-recruitment parameters

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

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

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

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

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

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

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

The equilibrium outputs are found when $|N_t - N_{t+1}| < \epsilon$ for some appropriately small $\epsilon > 0$. DDUST relies on the assumption that this occurs after *eqiter* years (100 years by default) of iterations. Users should validate this assumption with a convergence test. The outputs are then relabelled as

$$\overline{N} = N_t = N_{t-1} \tag{H.24}$$

$$\overline{B} = B_t = B_{t-1}. \tag{H.25}$$

Equilibrium spawning biomass is calculated as

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

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 H.3 are then

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

$$\beta = \frac{5h-1}{4hR_0} \tag{H.28}$$

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).

H.2 Statistical framework

H.2.1 Abundance indices

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

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

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,

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

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,

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

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

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

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

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

The predicted abundance index is therefore

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

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

H.2.2 Absolute biomass

The DDUST model also fits to one or more estimates of absolute vulnerable biomass (V). The model assumes a normal error structure with $\sigma = \sigma_{V_t}$ and $\mu = B_t$ and uses the following relationship between biomass and a biomass estimate,

$$B_t = V_t. \tag{H.35}$$

H.3 Likelihood components

The likelihood has five main components: abundance indices log-likelihood, vulnerable biomass estimate log-likelihood, recruitment deviation log-likelihood, penalties and priors. The abundance indices log-likelihood is

$$LL_I = \frac{\log(\sigma_I)}{2} + \sum_t \left[\frac{\left(\log(\hat{I}_t) - \log(I_t)\right)^2}{2\sigma_I} \right]. \tag{H.36}$$

The vulnerable biomass estimate log-likelihood is

$$LL_V = \frac{\log(\sigma_V)}{2} + \sum_t \left[\frac{(\log(V_t) - \log(B_t))^2}{2\sigma_V} \right]. \tag{H.37}$$

The recruitment deviation log-likelihood in REDDUST is

$$LL_R = \frac{\log(\sigma_R)}{2} + \sum_t \left[\frac{\left(\log(R_t^*) - \log(R_t)\right)^2}{2\sigma_R} \right]. \tag{H.38}$$

The recruitment deviation log-likelihood in DDUST is

$$LL_R = \frac{\log(\sigma_R)}{2} + \sum_t \left[\frac{\ln \eta_t^2}{2\sigma_R} \right]. \tag{H.39}$$

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

$$P_{\text{catch}} = \frac{1}{2} \sum_t \left[\frac{\left(\log(\frac{C_t}{1000}) - \log(\frac{B_t}{1000})\right)^2}{2\sigma_1} \right]. \tag{H.40}$$

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

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

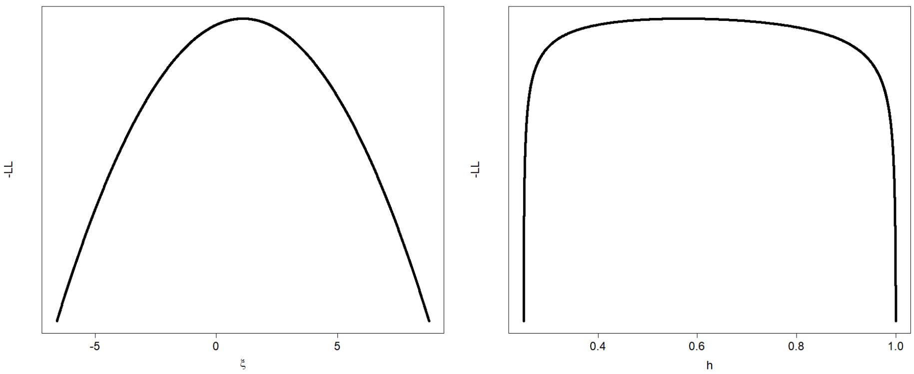
$$\xi \sim \text{Log-normal}(\mu_\xi = \log(3), \sigma_\xi^2 = 1). \tag{H.41}$$

Figure H.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

$$P_\xi = \frac{1}{2}\frac{(\xi - \mu_\xi)^2}{\sigma_\xi^2}, \tag{H.42}$$

$$P_\mu = \frac{1}{2}\frac{(\mu - \mu_\mu)^2}{\sigma_\mu^2}, \tag{H.43}$$

$$P_\kappa = \frac{1}{2}\frac{(\kappa - \mu_\kappa)^2}{\sigma_\kappa^2}. \tag{H.44}$$



(a) log-normal prior of transformed parameter ξ

(b) transformed prior of original parameter h

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

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

$$LL = LL_I + LL_R + P_{\text{catch}} + P_{\text{recruits}} + P_\xi + P_\mu + P_\kappa. \tag{H.45}$$