Stock assessment of Queensland east coast burrowing blackfish (*Actinopyga spinea*), with data to June 2023

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Queensland Government

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Contents

Summary

This stock assessment considered burrowing blackfish (*Actinopyga spinea*) as three distinct populations, one associated with Gould Reef (Gould), one associated with the Capricorn Bunker Group (Bunker), and one associated with Lizard Island (Lizard). For the Gould population, results indicate that biomass declined from an assumed unfished state in 1996 to between 51% and 101% at the end of July 2023. For the Bunker population, results indicate that biomass declined from an assumed unfished state in 1996 to potentially as low as 83% in 2022. The stock level for the Bunker population at the end of July 2023 was estimated to be between 51% and 101%. No stock assessment result is provided for Lizard and this is discussed in Appendix A

Burrowing blackfish is a species of sea cucumber from the family Holothuriidae that is found in north-eastern Australia, New Caledonia, and possibly other Melanesian countries. In Australia, burrowing blackfish distributions extend along the entire Great Barrier Reef. They often occur in shallow to deeper depths from 1 to 25 m in a variety of habitats such as reef flats and sand lagoons and bays. Like many commercially exploited sea cucumber species, the biology of burrowing blackfish is not well studied.

This is the first stock assessment conducted on Queensland east coast burrowing blackfish by Fisheries Queensland.

This stock assessment includes input data through to June 2023. All assessment inputs and outputs were referenced on a financial year basis (that is, 2023 means July 2022-June 2023).

This assessment used two different population models: a one-sex age-structured population model, and a delay-difference model. Both models used an annual time step and were fitted to standardised catch rates. The age-structured and delay-difference models produced similar results and the age-structured model was chosen for headline reporting.

The assessment incorporated commercial catch and effort data spanning 1996 to 2023 as well as length composition data and estimates of absolute abundance from recent surveys undertaken at Gould (2020), and Bunker (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 boiled and frozen weight for consistency with fishery reporting and management. Over the last 5 years, 2019 to 2023, the Gould stock total retained catch averaged 47 tonnes per year (17.625 tonnes boiled and frozen weight) (Figure 1), and the Bunker stock total retained catch averaged 64 tonnes per year (24 tonnes boiled and frozen weight) (Figure 2).

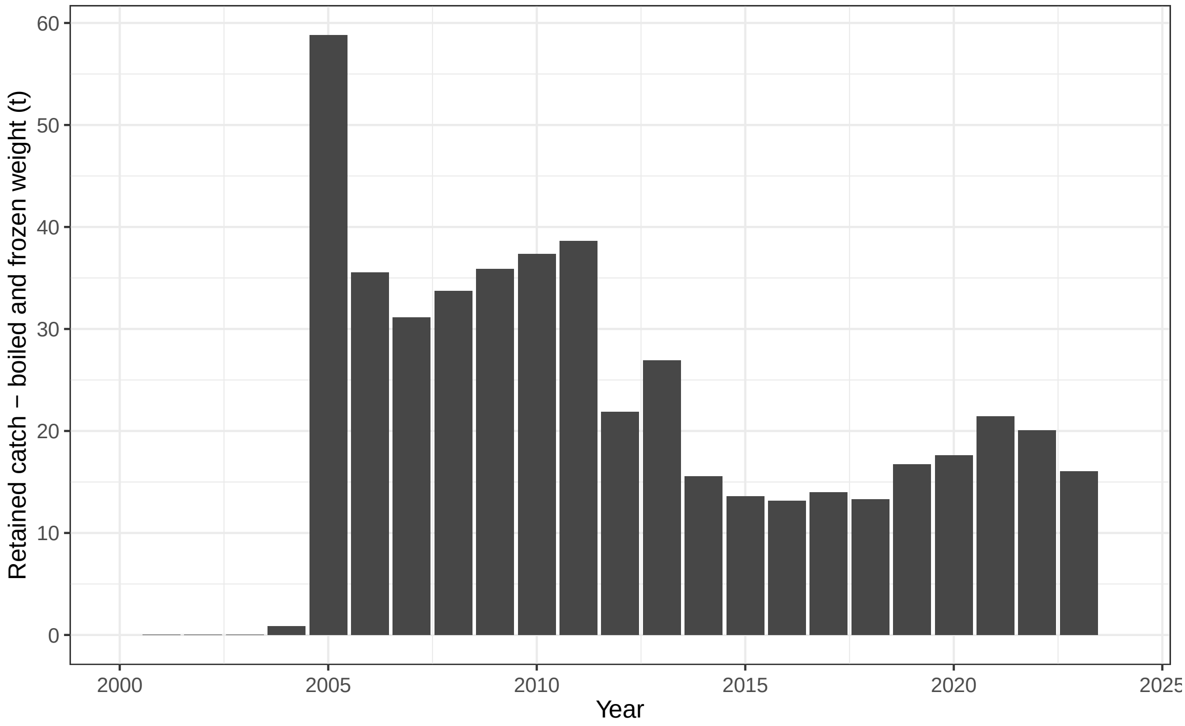

Figure 1: Annual estimated commercial retained catch between 2000 and 2023 for Gould in boiled and frozen weight. Catches from other sectors are not available but are considered negligible.

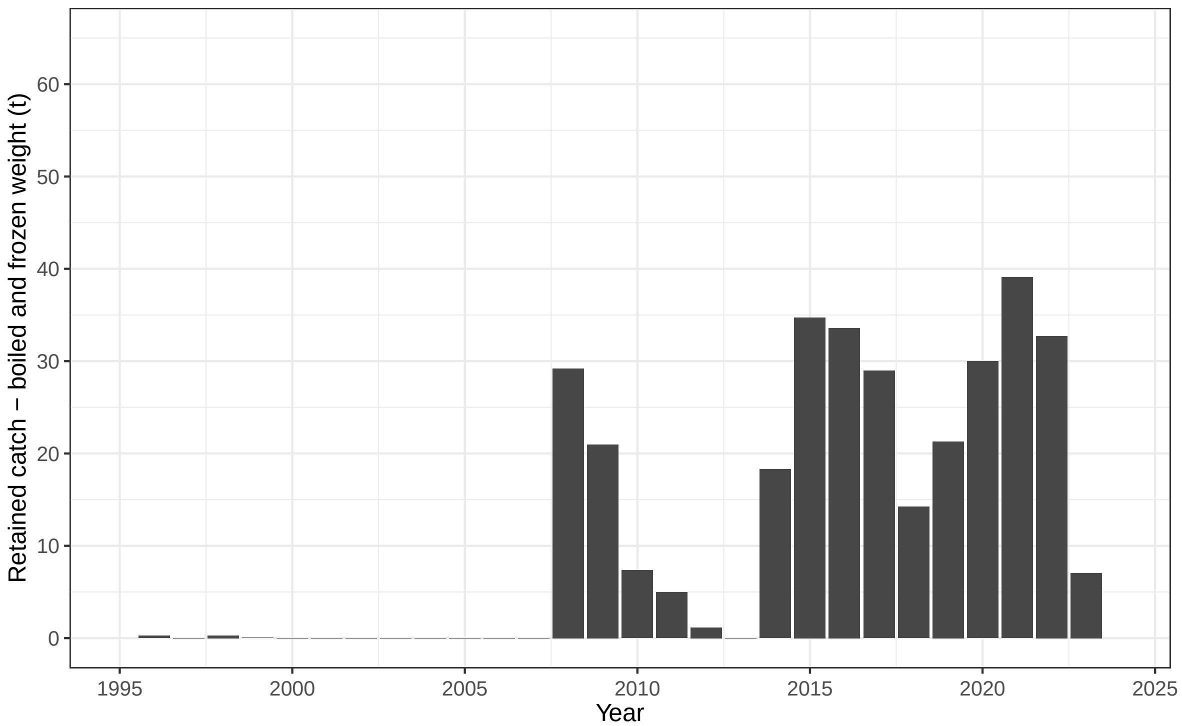

Figure 2: Annual estimated commercial retained catch between 1996 and 2023 for the Bunker in boiled and frozen weight. Catches from other sectors are not available but are considered negligible.

Commercial catch rates were standardised to estimate an index of abundance through time (Figure 3 and Figure 4). 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 and vessel were included as explanatory terms.

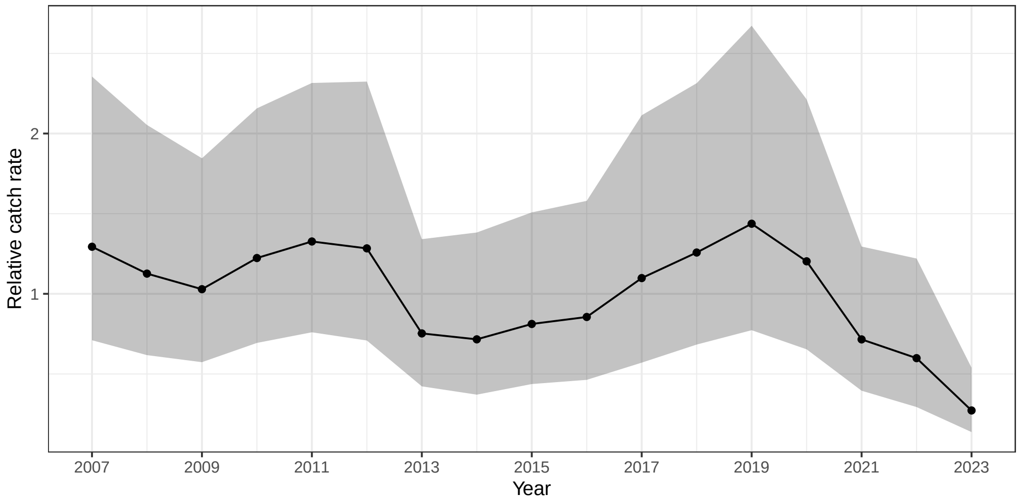

Figure 3: Annual standardised catch rates relative to average kg per hour (live weight) for the Gould stock between 2007 and 2023 .

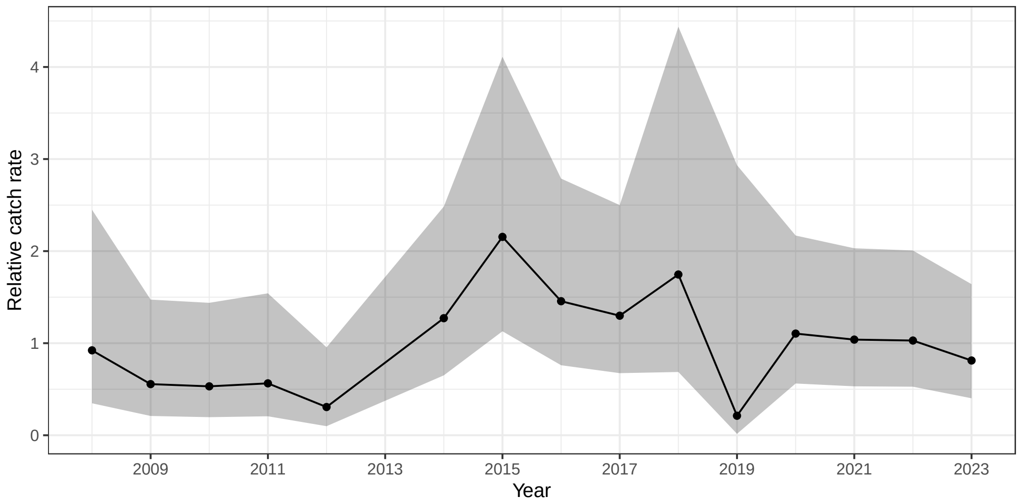

Figure 4: Annual standardised catch rates relative to average kg per hour (live weight) for the Bunker stock between 2008 and 2023 .

Up to fifteen scenarios 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 scenario results indicate that the Gould stock experienced a decline from the period 2000 to 2023 to reach 72% of unfished biomass (51–101% range across the 95 percent credible interval) (Figure 5 and Figure 6). The Bunker stock experienced a decline from the period 1996 to 2022 to reach 83% of unfished biomass. In 2023 the stock level was estimated to be 92% of unfished biomass (78–109% range across the 95 percent credible interval) (Figure 7 and Figure 8).

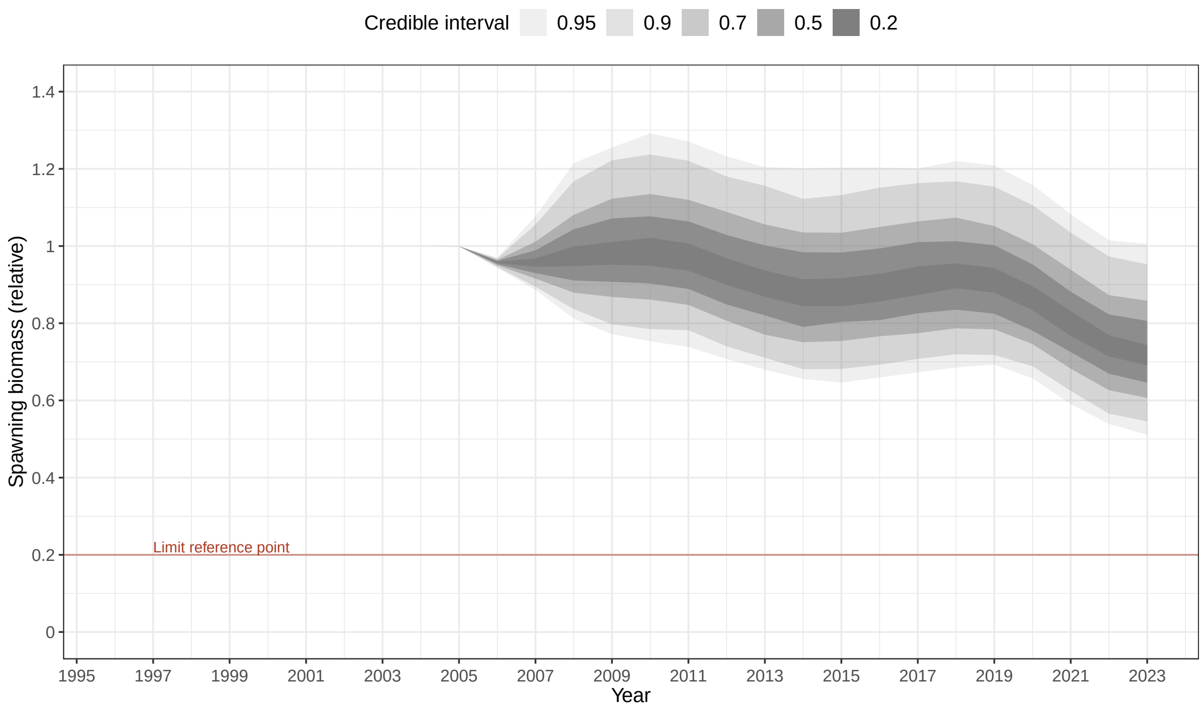

Figure 5: Estimated biomass trajectory relative to unfished from the base case Stock Synthesis model for the Gould stock, from 1996 to 2023.

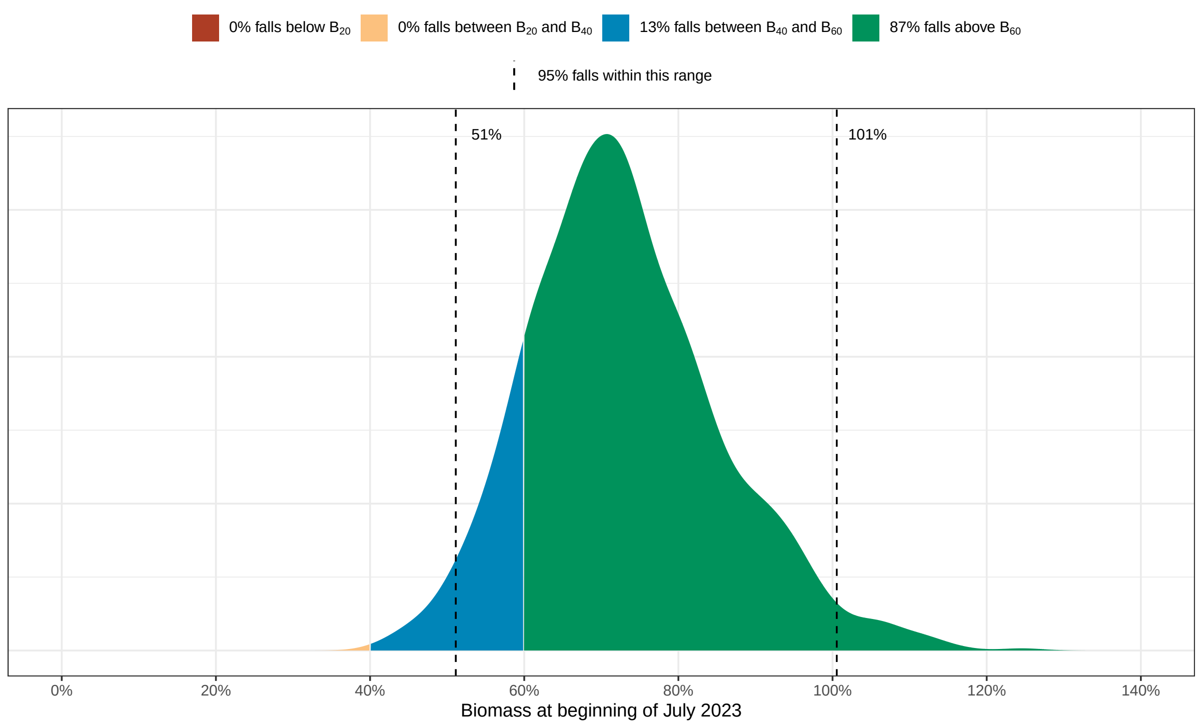

Figure 6: Probability distribution of the biomass ratio in 2023 for the base case Stock Synthesis model for the Gould stock with the credible interval and probability of biomass falling into the three categories indicated.

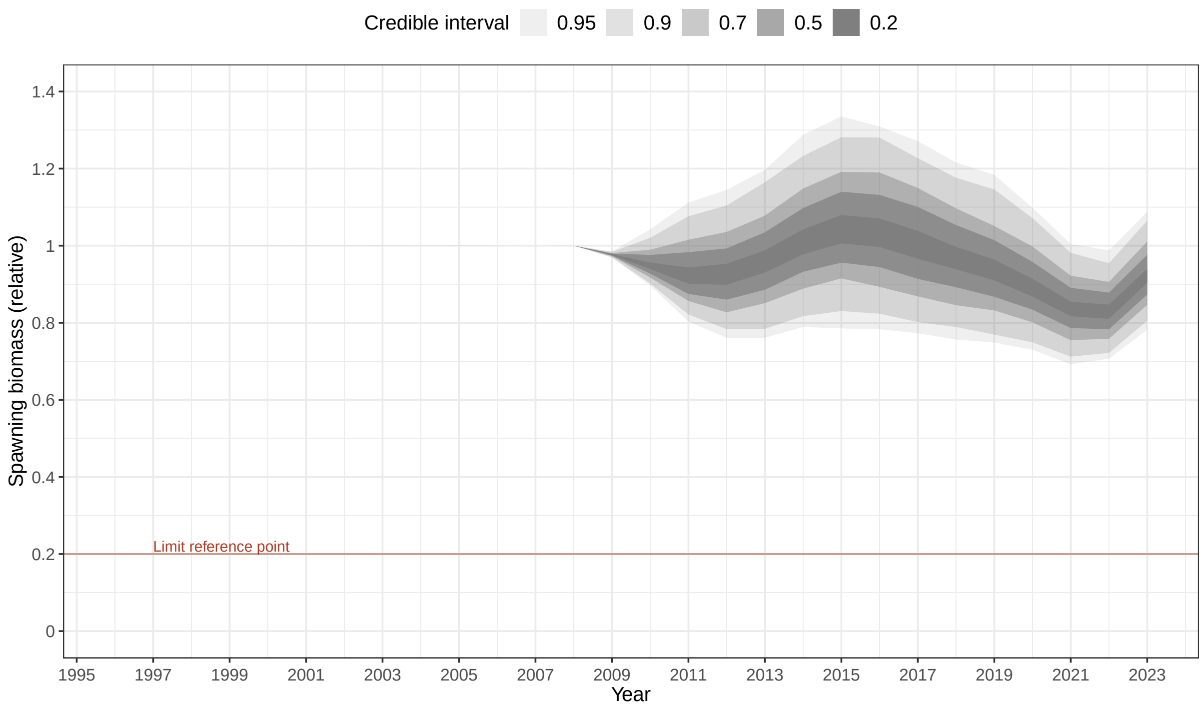

Figure 7: Estimated biomass trajectory relative to unfished from the base case Stock Synthesis model for the Bunker stock, from 1996 to 2023.

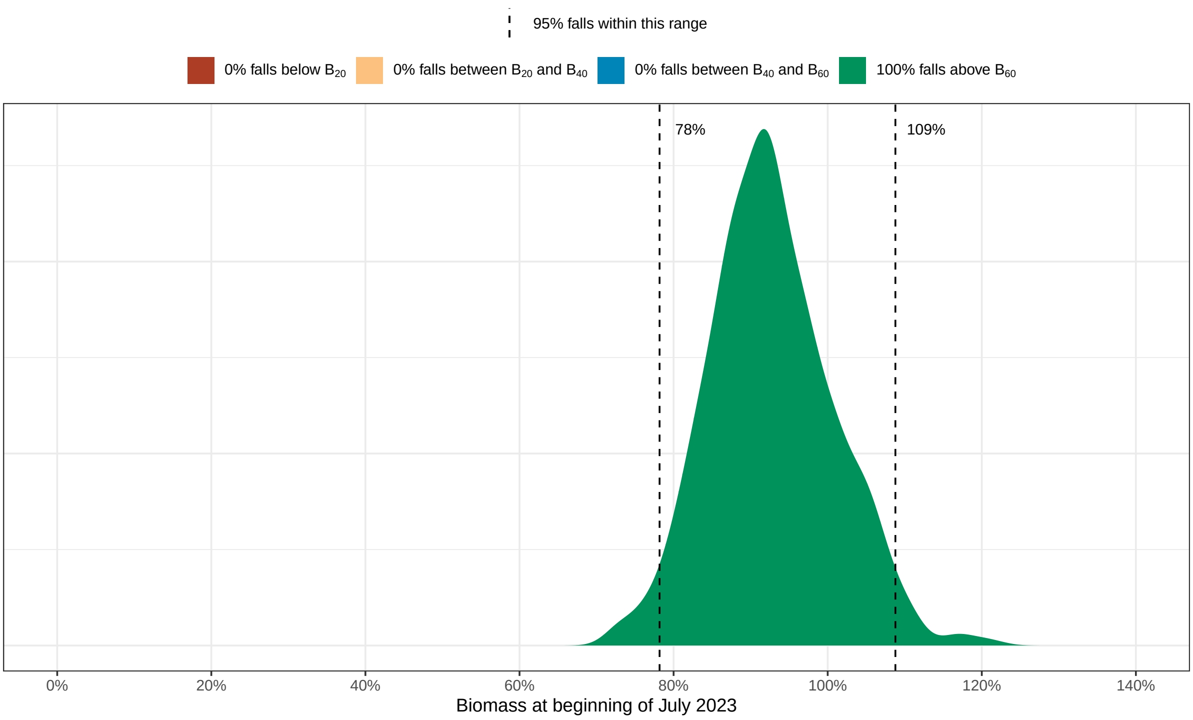

Figure 8: Probability distribution of the biomass ratio in 2023 for the base case Stock Synthesis model for the Bunker stock with the credible interval and probability of biomass falling into the the category indicated.

Table 1: Current and target indicators for the Queensland east coast burrowing blackfish Gould stock

Indicator	Value
Biomass ratio relative to unfished)	
Range (95% credible interval)	51–101%
Probability below 20%	0%
Probability between 20% and 40%	0%
Probability between 40% and 60%	13%
Probability above 60%	87%
Average five-year (2019 to 2023) retained commercial catch (boiled and frozen weight)	18 t

Table 2: Current and target indicators for the Queensland east coast burrowing blackfish Bunker stock

Indicator	Value
Biomass ratio relative to unfished)	
Range (95% credible interval)	78–109%
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)	24 t

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Glossary

BBZ	Burrowing blackfish zone
compulsory logbooks	the compulsory commercial logbook database managed by Fisheries Queensland
CI	credible interval
CV	coefficient of variation
DDUST	Delay-Difference with User Specified Timestep
fisher hour	a single day hour of fishing by an individual within a fishing operation. 'Fishing' includes all part of the days operations including search time, dive time and product processing time.
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	generalized linear model
GPS	Global Positioning System
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
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

Burrowing blackfish (*Actinopyga spinea*) is a species of sea cucumber from the family Holothuriidae that is found in northeastern Australia, New Caledonia, and possibly other Melanesian countries (Purcell et al. 2023). In Australia, burrowing blackfish distributions extend along the entire Great Barrier Reef (GBR), although this species is not ubiquitously distributed and instead occurs in discrete areas with high densities. It is often mistaken for a similar species, hairy blackfish (*A. miliaris*), to whom it is closely related. As a result, burrowing blackfish probably has an under-represented global distribution (Purcell et al. 2023). A key distinguishing feature between burrowing blackfish and hairy blackfish is their behaviour with burrowing blackfish (as the name suggests) burying itself in muddy-sand habitats. This can afford greater protection to fishing as it increases the cryptic component of the population that is more difficult to harvest (Friedman et al. 2011). Burrowing blackfish can occur in depths from 1 to 25 m in a variety of habitats such as reef flats and sand lagoons and bays (Purcell et al. 2023).

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 and undersize individuals. There is no available information on recreational nor Indigenous catches, however these are considered negligible. 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 effort spatially. Three burrowing blackfish zones (BBZ) (Lizard, Gould, and Bunker) are distinct from this arrangement. Each BBZ can be fished for an unlimited number of days each year but has a zone-specific catch trigger in place that was determined from earlier surveys (Leeworthy 2007a; Leeworthy 2007b; Leeworthy 2010). The fishery has a limited number of licences and limits to the number of divers in the water at one time. Burrowing blackfish in the QSCF have a minimum legal size (MLS) of 20 cm.

Burrowing blackfish are a Tier 1 species in the QSCF and have constituted the largest species catch since the 2005 season at an average of approximately 300 t live weight. This is three times larger than the second most caught species, white teatfish (*Holothuria fuscogilva*). However, burrowing blackfish is a lower value species in comparison to others in the fishery such as black teatfish (*H. whitemaei*), white teatfish and sandfish (*H. scabra*). Burrowing blackfish therefore constitute approximately 40% of total fishery value despite much larger catches than other species (Wolfe et al. 2022). This indicates that burrowing blackfish is only commercially profitable through high catch rates from fishing areas with high densities, such as the BBZ.

Table 1.1: Management changes applied to burrowing blackfish in the Queensland Sea Cucumber Fishery

Year	Fisheries management, regulations and operations
1988	Compulsory commercial catch logbook reporting commenced
1991	Introduction of quota

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Table 1.1 – *Continued from previous page*

Year	Fisheries Management, Regulations and Operations
1995	Introduction of logbook version BD01; number and weight required; fishery entry limited to existing licence holders
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 approximately 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 and burrowing blackfish zone (BBZ)
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 Burrowing blackfish identified as Tier 1 species Catch trigger levels applied. If exceeded a competitive TACC will be set at the prescribed trigger levels: Lizard = 120 t, Gould = 45 t or Bunker = 60 t
September 2021	Introduction of logbook version BD05 Commercial Logbook implemented to report estimated weights and number of containers

The purpose of this report is to fulfill parts a) and b) of condition 7 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 7 of the WTO application states that: "The Queensland Department of Agriculture and Fisheries must:

a) Ensure data from fishery independent surveys of Burrowing Blackfish at the Lizard, Gould and Bunker Reef Burrowing Blackfish Zones are representative of the fishery and used to inform a stock assessment for the species.

b) Undertake and publish the stock assessment for Burrowing Blackfish. The stock assessment must be independently peer reviewed and must be completed by 30 May 2024.

c) The outcomes of the stock assessment must be incorporated into the updated MSE. Implement any necessary changes to the total allowable catch (TAC) to ensure that rate of fishing mortality does not exceed that required to achieve the biomass target of 60% of unfished biomass for this species as detailed in the harvest strategy for the fishery."

Collaborative surveys between the QSCF and independent scientists were conducted at each of the three BBZ: Gould in 2019 (refered to as 2020 in this report based on model timestep) (Koopman et al. 2019), Lizard in 2022 (Koopman et al. 2022) and Bunker in 2023 (Koopman et al. 2023). 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. These surveys also provide empirical information on recent harvest rates for each stock based on the estimate of biomass and corresponding catch for each BBZ. Historical surveys were also undertaken for each stock: Gould in 2004, Bunker in 2009 and Lizard in 2005 (Leeworthy 2007a; Leeworthy 2007b; Leeworthy 2010). However, only the historical survey for Gould was included in this assessment due to large spatial differences in surveyed area for the remaining stocks.

An additional survey was undertaken for Lizard in March 2024 due to industry concern from the 2022 survey along with a voluntary fishing closure during this period (Koopman et al. 2022). However, a further stock decline occurred between the 2022 and 2024 surveys despite the absence of fishing (Koopman et al. 2024). Stock assessment modelling of the Lizard stock was unsuccessful and the recent findings are discussed in Appendix A. The implications of the Lizard survey results for Gould and Bunker are also considered in Appendix A.

Like many commercially exploited sea cucumber species, the biology of burrowing blackfish is not well studied with the rapid expansion of fishery outpacing the science (Friedman et al. 2011). Most of the information available for burrowing blackfish is related to its size. It has a maximum length of 43.5 cm (McSpadden at al. in prep), commonly grows to 27 cm and most individuals harvested are less than 1 kg in live weight (Purcell et al. 2023). Recent information on maturity from Williamson et al. in prep was available and was tested in this stock assessment. There is no information on growth, fecundity, or maximum age and previous research has used values based on expert elicitation from stakeholder workshops (Skewes et al. 2014). Given the small size of burrowing blackfish in comparison to other co-occurring sea cucumber species, they were assumed to have higher productivity through younger maximum ages (8 years) and a higher natural mortality (0.73 yr^{-1}) (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 for burrowing blackfish

This assessment applied and compared two different stock assessment models to burrowing blackfish from the Gould, and Bunker BBZ, treating them as independent stocks. 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 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 models. 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 for burrowing blackfish 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. It also does not model length-dependent 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 which is not available for burrowing blackfish. Assumed parameters must therefore be used in these models, which is not ideal.

The two stock assessment models were applied to both stocks using assumed growth information for Stock Synthesis. These 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 financial year data (July 1 to June 30 each year) up to the end of June 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 determine annual harvests. The assessment period commenced when harvests began (in 1996 and 2000, for Bunker and Gould respectively) up until and including 2023 based on available information.

Table 2.1: Data compiled for input into the population model

Type	Fishing season	Source
Commercial vessel data	1996–2023	Commercial logbook data collected by Fisheries Queensland.
Commercial buyer data	2001–2023	Buyer logbook data collected by Fisheries Queensland
Fishery independent survey data for Gould	2004 and 2020	Leeworthy (2007a), Koopman et al. (2019)
Fishery independent survey data for Bunker	2023	Koopman et al. (2023)

2.1.1 Regions

This assessment was grouped into regions (i.e, stocks) based on the burrowing blackfish zones (BBZ) outlined in the harvest strategy (Fisheries Queensland 2021). These zones form discrete management units that are outside of the RHA and can be fished every year for burrowing blackfish (Figure 2.1). They were established as burrowing blackfish occur in high densities within these zones and in much lower densities outside of them.

Preliminary information on stock structure from Williamson et al. in prep suggests that burrowing blackfish form a single biological stock across the GBR. However, there are large distances between each of these zones (Figure 2.1) and it is likely that recruitment is reasonably localised. Accordingly, burrowing blackfish stock structure is best described as Type B according to the Marine Stewardship Council population structure classification system: “A local population with partial isolation”. Whereby, fishing on the local population appears to have no effect on the dynamics of neighbouring populations, allowing for spatial management (MSC 2022). Therefore, the BBZ were modelled as separate management units (i.e. stocks). The intermittent areas between the BBZ were not included in this assessment as there are no biomass indices associated with these populations and low levels of catch. Therefore, any burrowing blackfish harvested through the RHA in the outlying areas were not modelled.

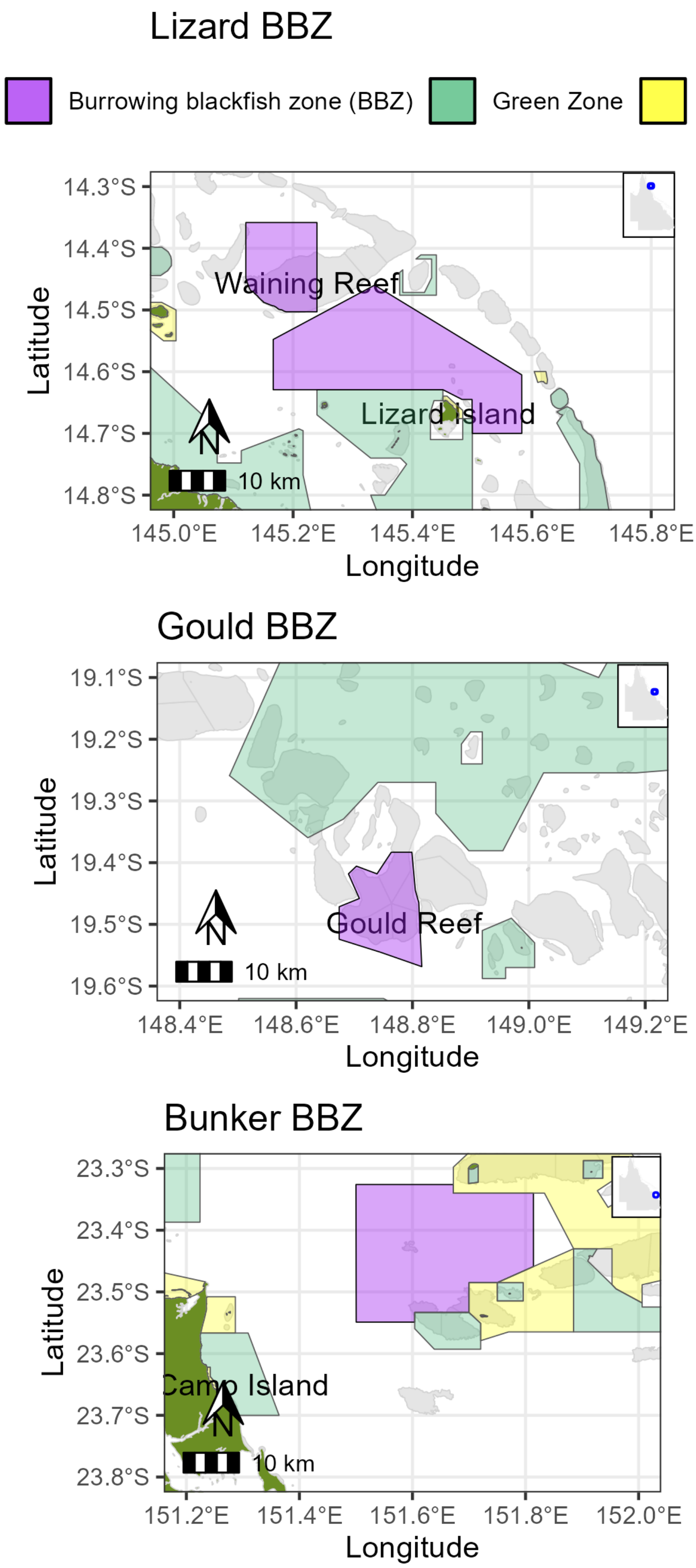

Figure 2.1: Map of the three Queensland Sea Cucumber Fishery burrowing blackfish zones (BBZ) and their location along the Queensland Coast.

Burrowing blackfish 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. Catches for burrowing blackfish largely occurred following the RAP's introduction and biomass surveys undertaken in the 2020, 2022 and 2023 seasons only surveyed small areas within green zones that were adjacent to each BBZ. This information was insufficient to allow spatially structured models that incorporate the green zones 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 the green zones that constitute 33% of the GBRMP.

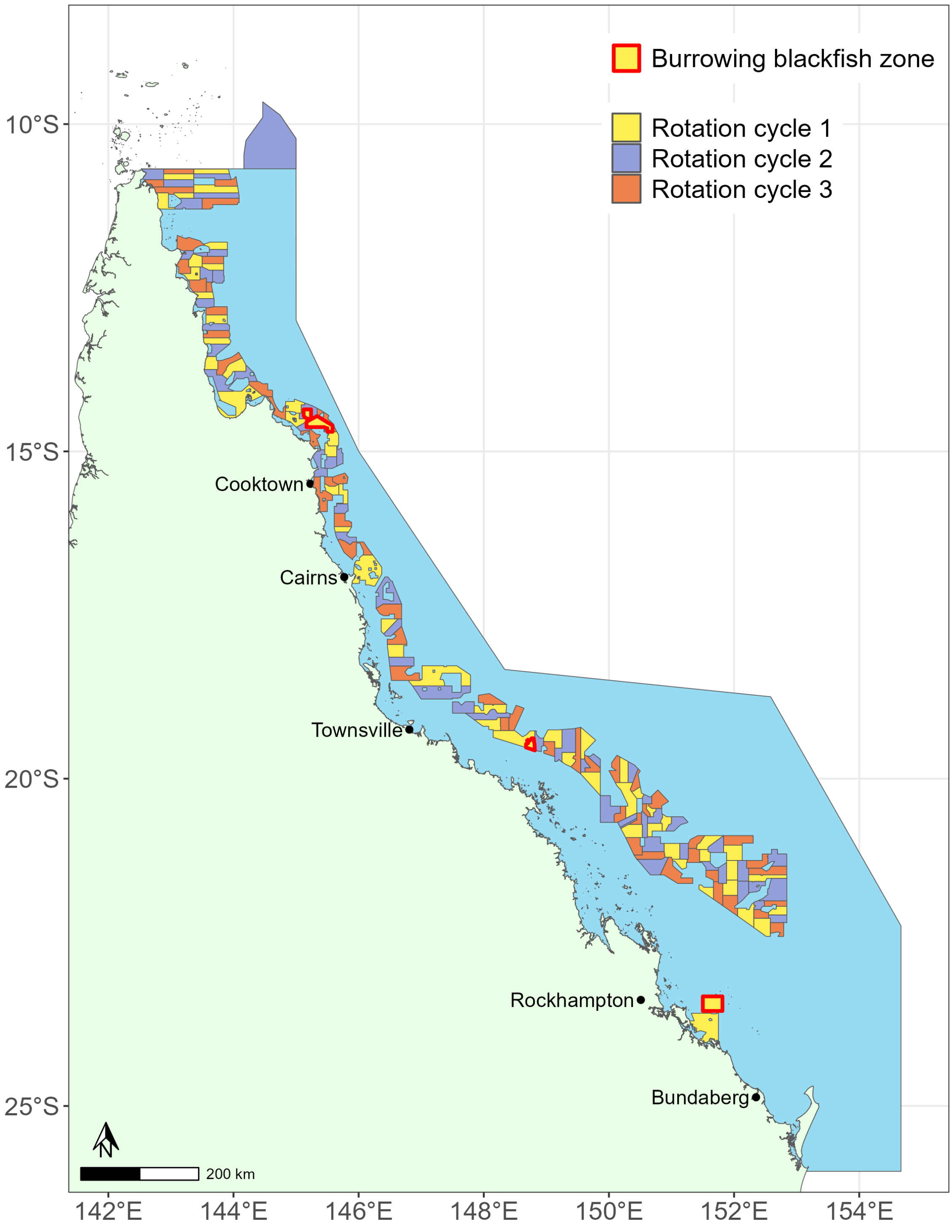

Figure 2.2: Map of the Queensland Sea Cucumber Fishery RHA zones and the locations of the burrowing blackfish zones (BBZ).

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 1996. 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/BBZ 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 QSCF 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 burrowing blackfish 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

Individual biomass surveys have been undertaken at each BBZ: Gould in October 2019 (2020 model timestep) (Koopman et al. 2019), Lizard in April 2022 (Koopman et al. 2022) and Bunker in January 2023 (Koopman et al. 2023). These surveys used a random stratified design undertaken across key habitats to determine the density of burrowing blackfish for different strata. These densities were then scaled to the total BBZ biomass according to the available habitat and corresponding burrowing blackfish 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.

The 2004 survey undertaken at Gould and 2005 survey at Lizard (Leeworthy 2007a; Leeworthy 2007b) used a gridded method to estimate biomass over a larger area than the recent surveys (Koopman et al. 2019; Koopman et al. 2022). The raw data from the 2004 and 2005 surveys were post-stratified so that biomass estimates could be produced for the same area as the recent surveys. Two subsequent surveys occurred at Gould in 2006 and 2009 using the same gridded design as the 2004 survey (Leeworthy 2007a). However, these surveys could not be included as low density sites were dropped over time, potentially biasing biomass estimates.

2.2 Harvest estimates

2.2.1 Commercial

Harvest estimates from 1996 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 90% of burrowing blackfish catch records reported as boiled and frozen with the remaining catches reported as salted weight. In recent years, almost all of the catches have been boiled and frozen product as this corresponds with the catch trigger levels (Fisheries Queensland 2021). The logbook reporting requirements have changed through time and therefore several data cleaning steps were undertaken:

- Some records prior to 2008 were reassigned as burrowing blackfish as they were initially mis-reported as ‘blackfish’ (*Actinopyga miliaris*) in logbooks. However, these were clearly burrowing blackfish given the locations and characteristics of the fishing events.

- Prior to 2009, neither RHA zone or BBZ were required in logbook returns. The BBZ was determined from the associated fishing grids when it was not reported.
- 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 burrowing blackfish from logbook and buyer return records where number and weight were reported.
- Logbook catches were scaled so that the total burrowing blackfish catch (all BBZ and RHA zones combined) matched the total catch from buyer returns for each year. Buyer returns do not include information on BBZ so statewide harvest levels were used for this scaling.
- Product weights (mostly boiled and frozen) were scaled to live weight based on the product conversion factors from the Torres Strait Bêche-de-mer Fishery (Murphy et al. 2021). For boiled and frozen catches, the salted weight conversion factor of 0.375 was applied given that it would provide the most conservative catch scaling (i.e. catches would be higher).

Retained catch estimates in live weight were used in the stock assessment models, while catch statistics are reported in boiled and frozen 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 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).

2.2.3 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 burrowing blackfish typically 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) of burrowing blackfish (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 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 fishers and grid cells that did not substantially contribute to the fishery, or that were not representative of the fishery, were removed prior to catch rate analysis per the following filters:

- The data were reduced to boats who fished in more than two years.

- The data were reduced to boats who fished a total of more than 100 kg.
- The data were reduced to daily catch records with catch consisting of more than 75% of burrowing blackfish.
- The data 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. 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 both stocks used a Gaussian distribution with a log-link function.

The R equation form of Gould GLM was:

$$\textit{weight} \sim \textit{year} + \textit{grid} + \textit{boat} + \textit{offset(ln(fisher.hours))} \tag{2.1}$$

The R equation form of Bunker GLM was:

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

where the GLM type and variables were:

- *weight*: daily catch per fisher hour (weight)
- *year*: fishing year 2007 to 2023 (factor) for Gould, fishing year 2008 to 2023 (factor) for Bunker
- *boat*: anonymous codes for different operations (factor)
- *grid*: fishing grid (factor)
- *offset(ln(fisher.hours))*: model offset using fishing effort an 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 burrowing blackfish catch in weight per fisher-operation-hour. The prediction settings for the annual index of burrowing blackfish abundance by year, over steps A and B, were:

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

2.3.2 Biomass estimates

The surveys provided a single estimate of biomass in live weight (tonnes) for each stock (Koopman et al. 2019; Koopman et al. 2023). 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 is defined in each model.

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 for burrowing blackfish were specified as single sex models. The legal-sized biomass (i.e., fishable biomass) of burrowing blackfish is defined as the component of the population above the 20 cm MLS. The surveyed biomass estimates match neither of these biomass definitions, which was addressed by estimating the length selectivity for each survey 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 further refinements to the surveyed biomass inputs. Legal-sized biomass was determined by transforming the length composition to a weight composition using the weight-length relationship (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 for each survey. This became the biomass input for the DDUST models. The coefficient of variation (CV) for the surveyed biomass was maintained for the legal-sized biomass and also input to DDUST as a variance estimate.

2.4 Biological relationships

2.4.1 Weight-length relationship

The weight-length relationship was available from the Gould survey (Koopman et al. 2019):

$$W_L = W_\alpha \times L^{W_\beta} \tag{2.3}$$

where W_L is average weight (kg) at total length L (cm), W_α = 0.0013 and W_β = 1.949.

2.4.2 Maturity and fecundity

The length-at-maturity of burrowing blackfish is required by Stock Synthesis. Maturity was therefore specified with preliminary information from Williamson et al. in prep with the lengths-at-50% and 95%-mature (L_{50} and L_{95}, respectively) set at 19.75 cm and 27.45 cm. The sensitivity of the Stock Synthesis model to these values was tested through alternate values (Section 2.5.7).

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

$$P(L) = \left(1 + \exp^{-\ln(19)\left(\frac{L-L_{50}}{\Delta L}\right)}\right)^{-1} \tag{2.4}$$

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

There is no information on fecundity for burrowing blackfish. Therefore, fecundity was pre-specified to occur linearly with length.

Maturity and fecundity estimates are not required by DDUST and therefore the assumed values for fecundity 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:

$$L_a = L_\infty \left(1 - \exp^{-\kappa(a-a_0)}\right) \tag{2.5}$$

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 also not available for burrowing blackfish. Therefore, these parameters were pre-specified with L_∞ as the maximum length of 38 cm (Skewes et al. 2014), a_0 as zero and κ as 0.3 yr^{-1}. These parameters were chosen as they provided a growth trajectory that predicted an age-at-maturity (2 - 3.5 years) and longevity (8 years) that matched those specified in the Management Strategy Evaluation (MSE) undertaken by Skewes et al. (2014). The sensitivity of the Stock Synthesis model to these assumed parameters was tested through alternate values (Section 2.5.7).

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:

$$\rho = 1 - \frac{w_r - w_{r-1}}{w_\infty - w_{r-1}}. \tag{2.6}$$

Weight-at-recruitment (w_r) and asymptotic weight (w_∞) were pre-specified using the weight-length relationship with the MLS of 20 cm and maximum length of 38 cm, respectively. Weight-pre-recruitment (w_{r-1}) was approximated using the weight-length-relationship and a length of 14 cm, 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 from each survey (Koopman et al. 2019; Koopman et al. 2023) were input to the Stock Synthesis model in two-cm length bins. No age data were available. Sea cucumbers can truncate and elongate their lengths, potentially biasing length compositions. This was addressed by double measuring a small sample of burrowing blackfish on the sea floor and again in the boat (Koopman, unpublished data). While differences in individual lengths occurred, the resulting length compositions between measurements were not significantly different. Therefore, the use of length composition data for burrowing blackfish was deemed appropriate.

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 burrowing blackfish 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 I.

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 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 1996 for Bunker and 2000 for Gould.
- Stocks within each BBZ are reproductively isolated from other populations of burrowing blackfish.
- There is no migration into or out of BBZ.
- The instantaneous natural mortality rate does not depend on length, age, year or sex.
- 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 2.2.

The natural logarithm of unfished recruitment ($ln(R_0)$) was estimated within both the DDUST and Stock Synthesis models. However, the definition of a recruit is different within each model with age-zero recruits estimated by Stock Synthesis and recruits reaching the MLS of 20 cm estimated by DDUST. Therefore, the two parameters are not comparable between models.

Beverton-Holt stock recruitment steepness (h) was fixed at a pre-specified value. Steepness is a metric relating to the productivity of the stock. Specifically, h refers to the fraction of recruitment from a virgin population that is obtained when the population is at 20% of virgin spawning biomass (Lee et al. 2012). For the base case, h was pre-specified to the (natural scale) initial value of 0.3, based on prior knowledge that sea cucumber species often have low biological productivity and the recovery of overfished populations is often slow (Uthicke et al. 2004). Alternate values of h were included in sensitivity testing (details in Section 2.5.7). These values of h were the same for both stocks and applied to both the DDUST and Stock Synthesis models.

Natural mortality (M) was pre-specified in the model as 0.73 yr^{-1}, as per the MSE undertaken by Skewes et al. (2014). Alternate values of M were included in sensitivity testing (details in Section 2.5.7). These values of M were the same for both stocks and applied to both the DDUST and Stock Synthesis models.

Logistic length-based selectivity parameters were estimated in the model for the recent 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. The length compositions for Bunker were determined from measurements taken from the boat rather than the sea floor (Koopman et al. 2023). Therefore, a sensitivity scenario was applied where length measurements were increased by 20% to test whether size truncation could have affected the stock assessment results. However, this adjustment was not accepted for the base case model given the double measurement analysis described previously (Koopman, unpublished data). Length composition data were unavailable for the 2004 Gould survey but the results presented in the report suggest that the measurements were smaller than those in 2020 (Leeworthy 2007a; Koopman et al. 2019). Therefore, a pre-specified selectivity with a Size_inflection_Survey 10 cm shorter than that estimated for the 2020 survey was applied. This value was chosen based on visual inspection of figures presented in Leeworthy (2007a) and through a model tuning process that produced an improved fit to both survey estimates. Attempts to estimate the survey selectivity in 2004 produced poorer fits than using a pre-specified value.

Additional variance was estimated for catch rate indices to ensure that the models achieved an optimal fit to biomass. 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 both stocks and applied to both the DDUST and Stock Synthesis models (details in Section 2.5.7).

Recruitment deviations were estimated from the first year that catch rates were fit to for each stock, until the final model year. Recruitment variation (σ_R) was pre-specified as 0.3 for both stocks. This value was selected as it prevented over-fitting to catch rate indices and maintained a relative biomass trajectory that did not unreasonably exceed the unfished biomass levels. 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 2.5.7) 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 burrowing blackfish models. Single pre-specified values indicate a shared value across both stocks.

Parameter	Pre-specified value	Treatment	Model inclusion	Description
Fishery constants				
Start year Gould Bunker	 2000 1996	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	0.3	Pre-specified	Stock Synthesis/ DDUST	Variability of the rec devs around the stock recruitment relationship
h	0.3	Pre-specified	Stock Synthesis/ DDUST	Beverton-Holt steepness (h)
Rec devs first year Gould Bunker	 2005 2008	Pre-specified	Stock Synthesis/ DDUST	First year to estimate recruitment deviations
Length-to-weight				
W_α	0.0013	Pre-specified	Stock Synthesis/ DDUST	Weight-length relationship in kg and cm (Koopman et al. 2019)
W_β	1.949	Pre-specified	Stock Synthesis/ DDUST	Weight-length relationship in kg and cm (Koopman et al. 2019)
Growth parameters				
L_∞	38 cm	Pre-specified	Stock Synthesis	Asymptotic length for von Bertalannfy growth model; approximated
κ	0.3 yr^{-1}	Pre-specified	Stock Synthesis	Growth coefficient for von Bertalannfy growth model; approximated
a_0	0	Pre-specified	Stock Synthesis	Age-at-length zero for von Bertalannfy growth model; approximated
Other parameters				
M	0.73 yr^{-1}	Pre-specified	Stock Synthesis/ DDUST	Natural mortality (Skewes et al. 2014)
L_{50}	19.7 cm	Pre-specified	Stock Synthesis	Length-at-50%-maturity; Williamson et al. in prep
L_{95}	27.45 cm	Pre-specified	Stock Synthesis	Length-at-95%-maturity; Williamson et al. in prep

2.5.5 Parameter estimation

A Markov chain Monte Carlo (MCMC) was performed on all scenarios using 10,000 iterations (2,000 warm-up) and 3 chains for DDUST and 10,000 iterations (2,000 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 Appendices E, F). 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.

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 Model weighting

No formal model weightings were applied to the stock assessment models. However, the use of additional variance on catch rates in each model is a form of data weighting that down-weights the commercial catch rates. This is part of the model estimation process and places greater emphasis on the biomass estimates. The impact of the additional variance on catch rates was sensitivity tested as a scenario.

2.5.7 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 the 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. These alternative values test the sensitivity of the Stock Synthesis and DDUST models to that pre-specified value.
  - "Low": 0.2

- "High": 0.4

- **Natural mortality (*M*):** Natural mortality was pre-specified in the models as 0.73 yr^{-1}, as per the MSE undertaken by Skewes et al. (2014). Two lower values were tested as alternatives. The 'Mid' value of 0.55 yr^{-1} 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}
  - "Mid": 0.55 yr^{-1}

- **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.
- **Growth:** As no growth information is available for burrowing blackfish, 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:
  - "Fast": L_∞ = 35 cm; κ = 0.4 yr^{-1}; a_0 = 0
  - "Slow": L_∞ = 45 cm; κ = 0.2 yr^{-1}; a_0 = 0

  Similarly, the pre-specified length of 14 cm 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:** Maturity information was available from recent data from Williamson et al. in prep (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} = 12 cm; L_{95} = 25 cm
  - "Late": L_{50} = 20 cm; L_{95} = 32 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 8 years, as per Skewes et al. (2014). This was further sensitivity tested by using an older value of 20 years.

- **Shrinkage adjustment:** The length measurements from the Bunker survey were increased by 20% to determine the potential impact of size truncation occurring through measurements taken on the vessel. These length adjustments were used to determine length compositions for Stock Synthesis .

- **Spawner recruitment relationship:** The base case spawner recruitment in Stock Synthesis was given by the standard Beverton Holt relationship. This was sensitivity tested by using the Ricker relationship for spawner recruitment.

Full outputs of these sensitivity model scenarios are available in Appendices G and H. A summary of these scenarios and their numbering in Figures 3.15 and 3.20 is summarised in Table 2.3.

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

Scenario	Stocks	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	Slower growth
10	All	Stock Synthesis and DDUST	Faster growth
11	All	Stock Synthesis	Earlier maturity
12	All	Stock Synthesis	Later maturity
13	All	Stock Synthesis	Older plus group
14	All	Stock Synthesis	Ricker recruitment relationship
15	Bunker	Stock Synthesis	Shrinkage adjustment applied to length composition data

3 Results

Model inputs are described for burrowing blackfish for both stocks. Outputs relate to the Scenario 1—the 'base case' (defined in Section 2.5.7) for the Stock Synthesis models. The results from the base case DDUST models are compared to the Stock Synthesis relative biomass results in Figures 3.16 and 3.21. The complete results from the DDUST base case model are shown in Appendix D. Results for all Stock Synthesis scenarios are presented in Appendix G and all DDUST scenarios are presented in Appendix H.

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 each stock in Figures 3.1 and 3.2.

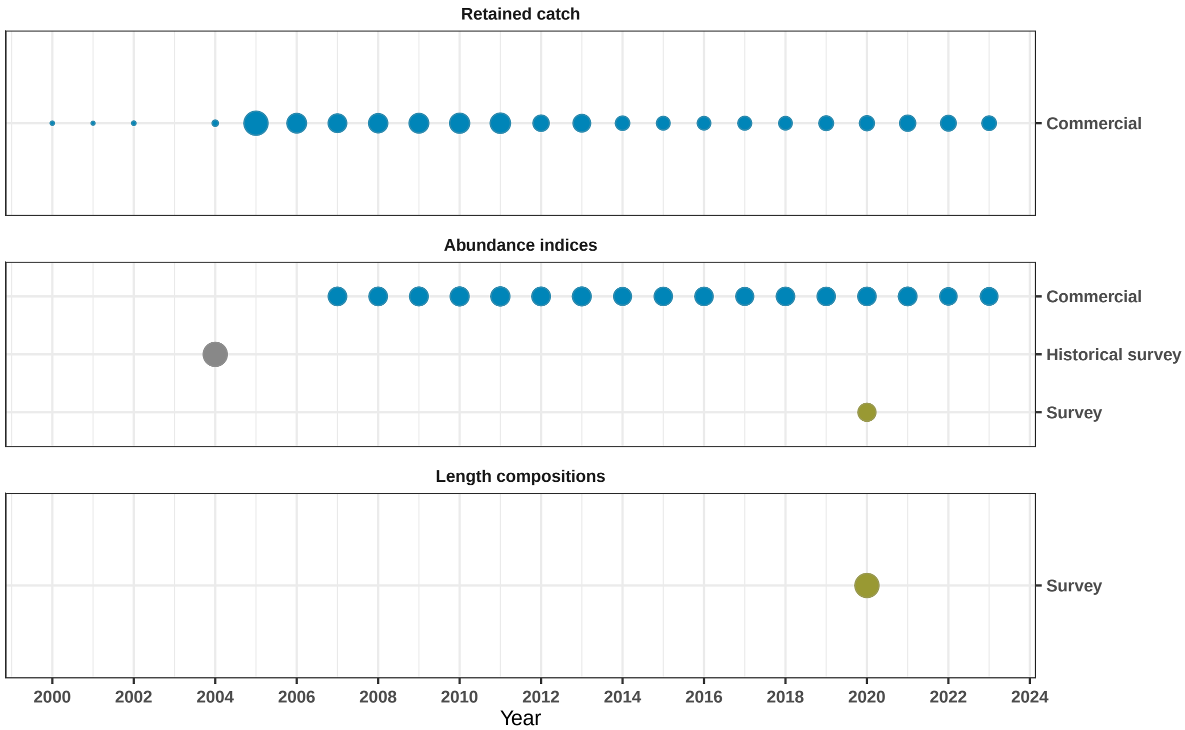

Figure 3.1: Data presence by year for each category of data type for Gould.

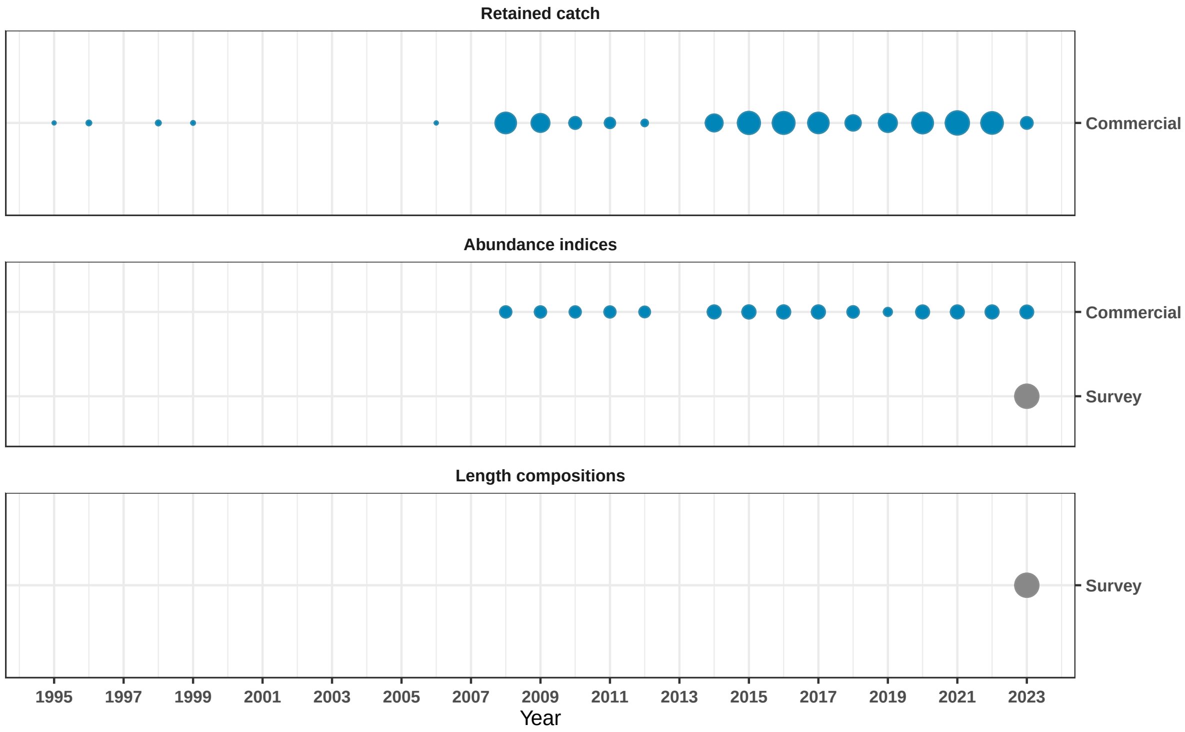

Figure 3.2: Data presence by year for each category of data type for Bunker.

3.1.2 Retained catch estimates

Total annual retained catch from the commercial sector for the Gould stock is shown in Figure 3.3. The retained catch of the Gould stock peaked in 2005 at 59 t (boiled and frozen weight). Over the last 5 years (2019 to 2023) total retained catch averaged 18 t per year (boiled and frozen weight). Total annual retained catch from the commercial sector for the Bunker stock is shown in Figure 3.4. The retained catch of the Bunker stock peaked in 2021 at 39 t (boiled and frozen weight). Over the last 5 years (2019 to 2023) total retained catch averaged 24 t per year (boiled and frozen weight).

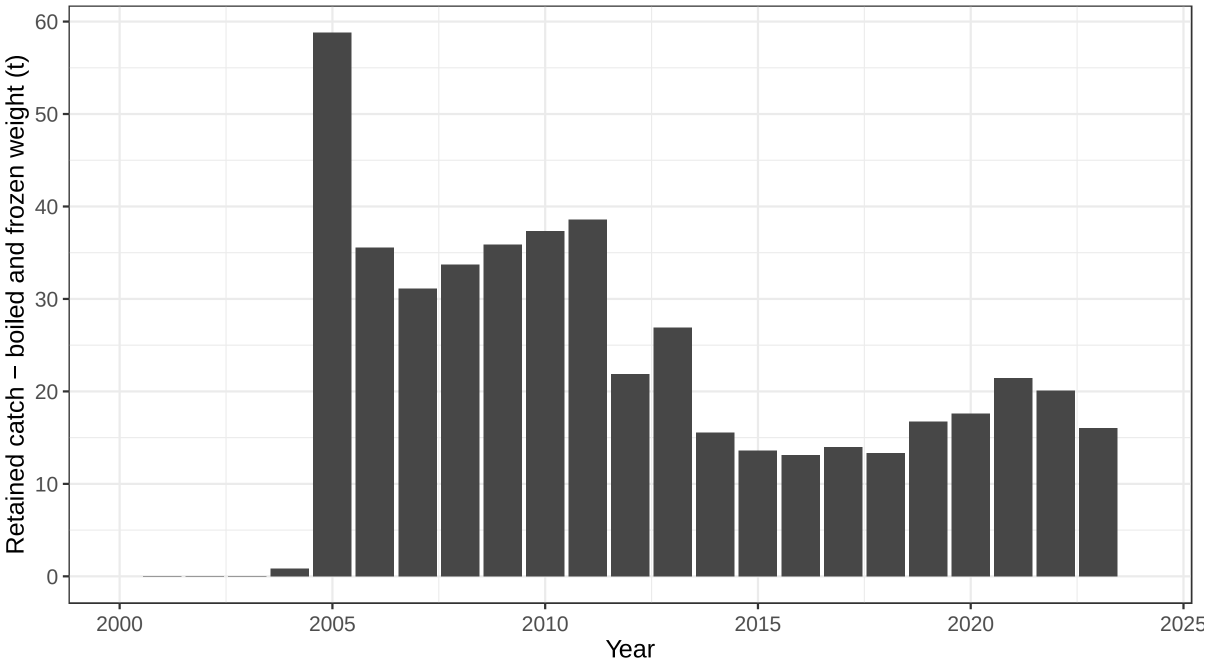

Figure 3.3: Annual estimated commercial retained catch between 2000 and 2023 for Gould in boiled and frozen weight. Catches from other sectors are not available but are considered negligible.

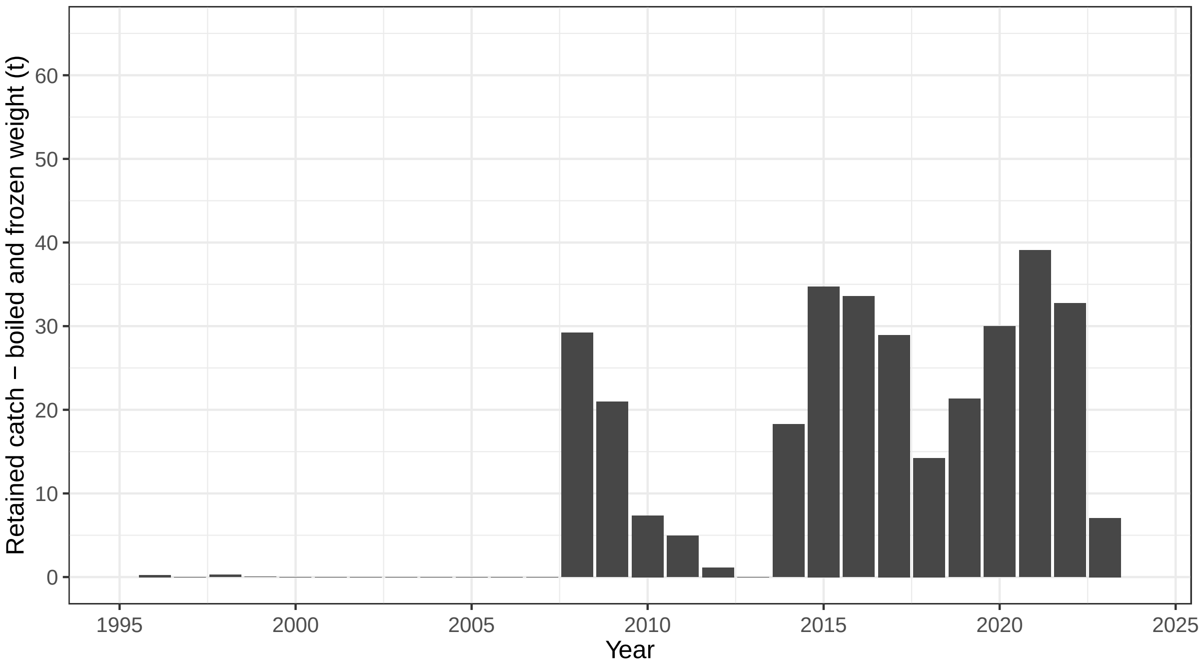

Figure 3.4: Annual estimated commercial retained catch between 1996 and 2023 for the Bunker in boiled and frozen weight. Catches from other sectors are not available but are considered negligible.

3.1.3 Unstandardised catch rates

The Gould stock generally had a higher catch rate than the Bunker stock, and had an average catch rate greater 1000 kg per day in most years. A declining catch rate trend has been occurring for Gould since 2020, with 2023 being the lowest on record and the first year with an average less than 1000 kg per day since 2009 (Figure 3.5). The catch rate for Bunker has been relatively stable through time with a slight increasing trend. Since 2014, the average catch rate for Bunker has been approximately 1000 kg per day (Figure 3.5).

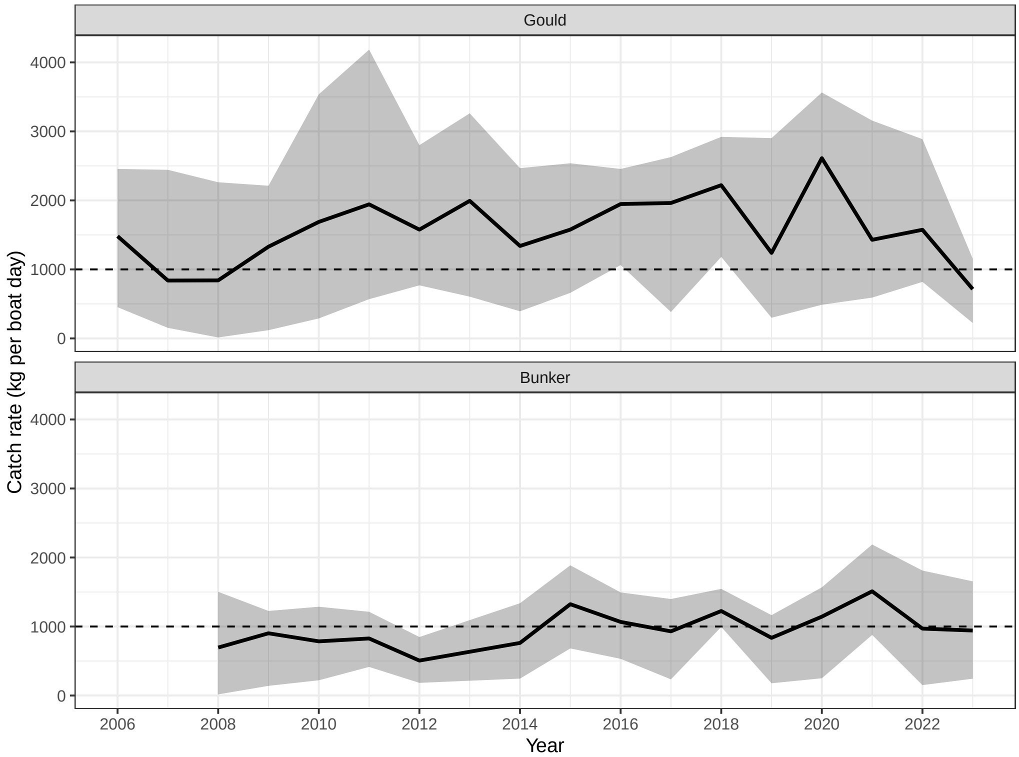

Figure 3.5: Unstandardised catch rates between 2006 and 2023 for Gould and Bunker stocks (kg per boat day). Grey shading present 95 percent CI. Dashed line indicates an average annual catch rate of 1000 kg per day.

3.1.4 Standardised catch rates

Standardised catch rates had a generally stable trend for Bunker with some fluctuations occurring across each time series (Figure 3.7). Standardised catch rates for Gould were also generally stable with minor fluctuations, until 2020 when four years of consecutive declines occurred. This decline was greater than the corresponding trend in unstandardised catch rates over these years (Figure 3.6). The standardised catch rate in 2023 for Gould was the lowest estimated (Figure 3.5, 3.6).

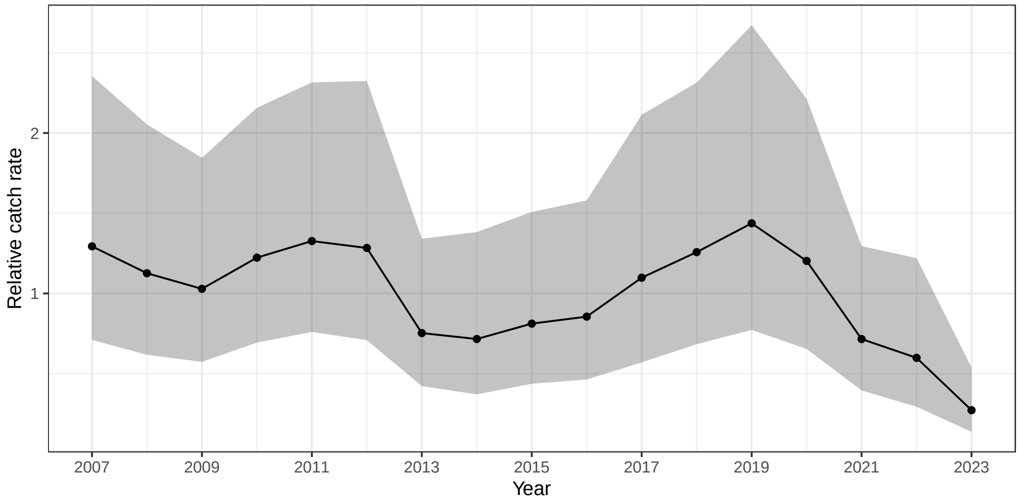

Figure 3.6: Annual standardised catch rates relative to average kg per hour (live weight) for Gould between 2007 and 2023 .

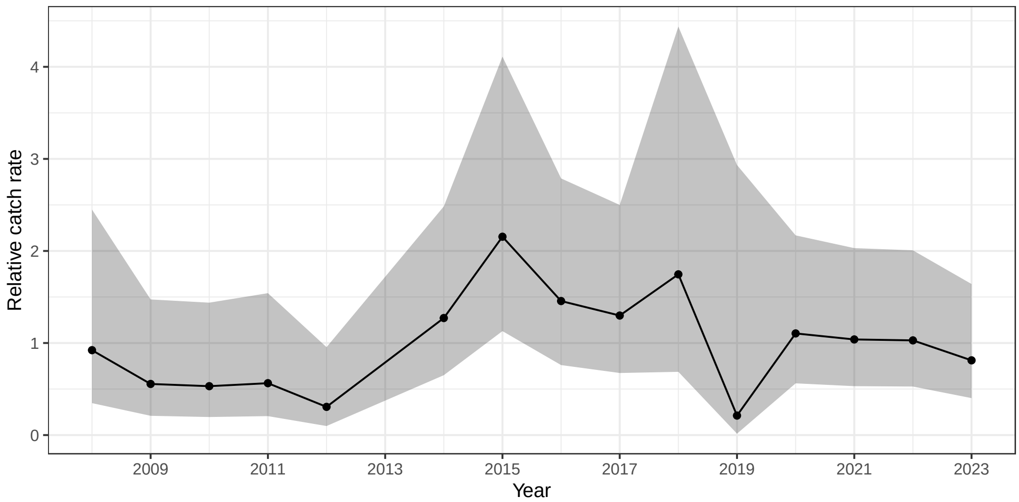

Figure 3.7: Annual standardised catch rates relative to average kg per hour (live weight) for Bunker between 2008 and 2023 .

3.1.5 Length compositions

Length structures from the surveys were mostly above the MLS of 20 cm (Figure 3.8, Figure 3.9).

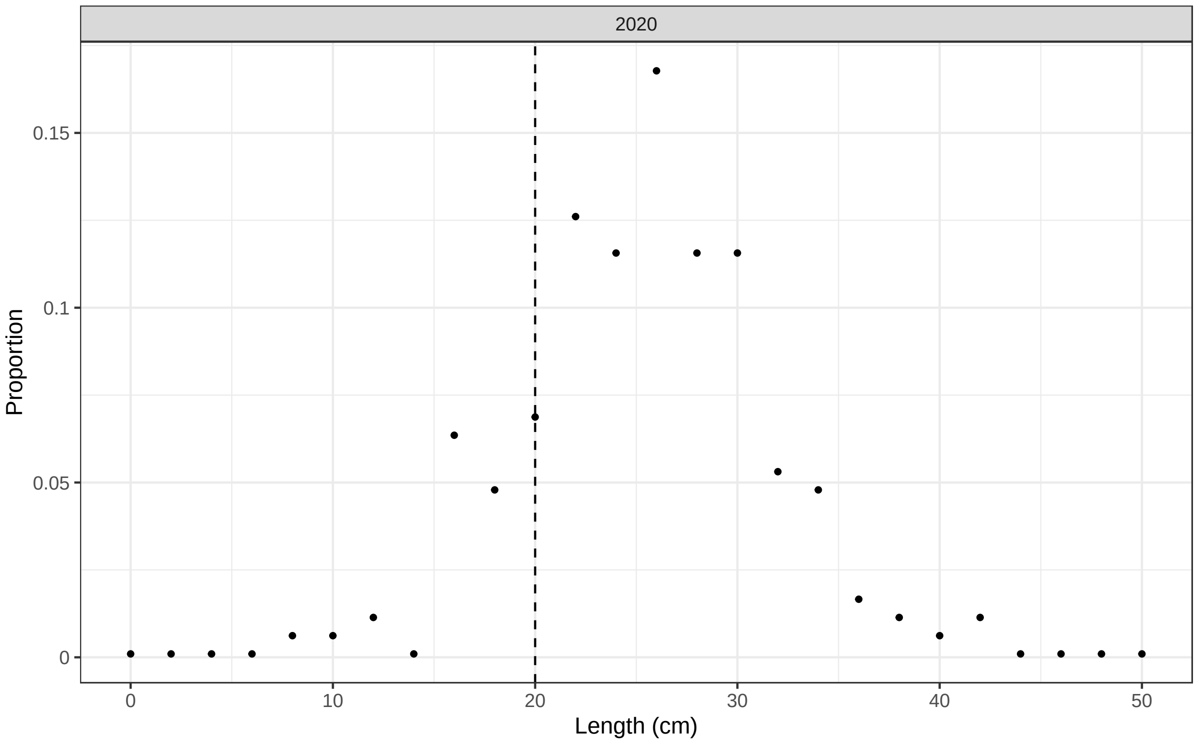

Figure 3.8: Length structures for the 2020 survey for the Gould stock. The dashed vertical line indicates the MLS of 20 cm.

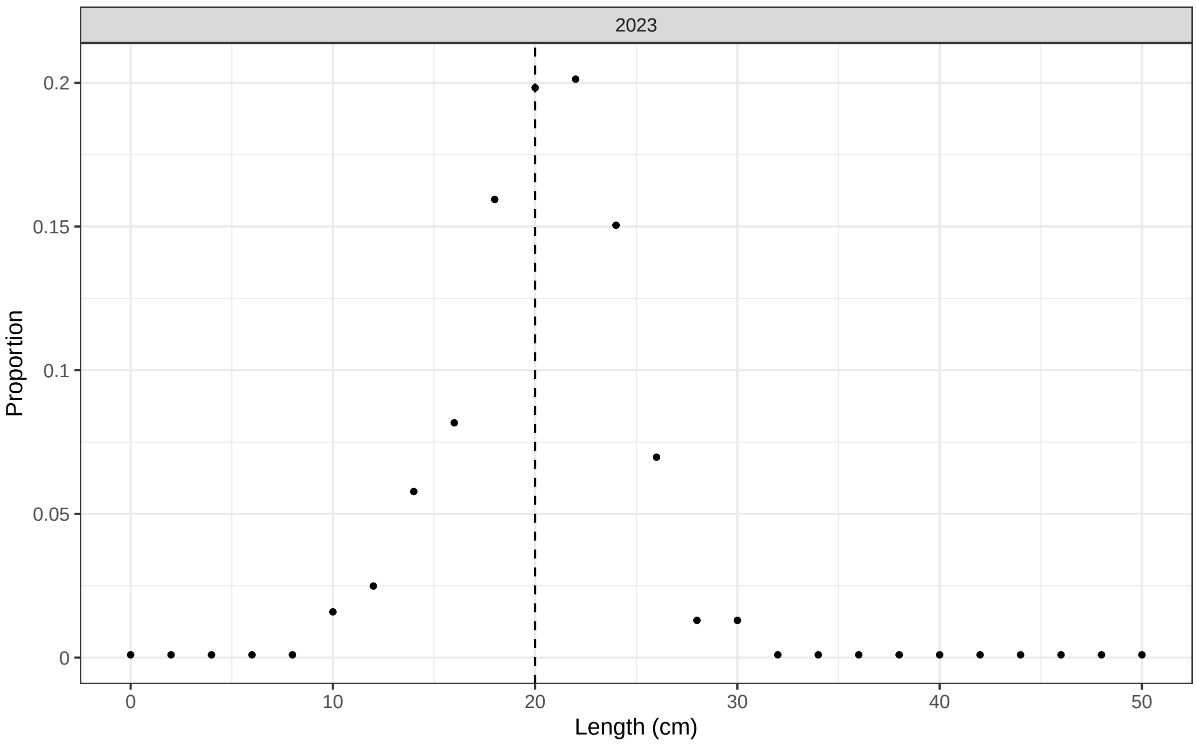

Figure 3.9: Length structures for the 2023 survey for the Bunker stock. The dashed vertical line indicates the MLS of 20 cm.

3.2 Model outputs

3.2.1 Model parameters

A number of parameters were estimated within the models for each stock (Tables 3.1 and 3.2). Model parameters for each scenario are plotted in Appendices G and H.

Table 3.1: Summary of parameter estimates from the base case Stock Synthesis and DDUST models for Gould 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◇	9.6 (0.14)	7.68 (0.09)
Survey selectivity inflection (cm)	24 (2.3)	
Survey selectivity width (cm)	8.5 (2.43)	
Catch rate variance (Q_extraSD in Stock Synthesis; σ_I in DDUST)	0.25 (0.08)	0.37 (0.08)

◇ 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 Bunker 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◇	9.57 (0.14)	7.57 (0.12)
Survey selectivity inflection (cm)	16.73 (1.46)	
Survey selectivity width (cm)	5.71 (2.42)	
Catch rate variance (Q_extraSD in Stock Synthesis; σ_I in DDUST)	0.13 (0.11)	0.59 (0.13)

◇ 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 for the base case models and most model scenarios. The scenario without additional catch rate variance (Scenario 8) showed overfitting to catch rates resulting in poorer fits to biomass for Gould by DDUST and Stock Synthesis and for Bunker by DDUST (Appendices G and H).

3.2.3 Selectivity

Survey length selectivity of burrowing blackfish was estimated within the Stock Synthesis model for both stocks in the most recent survey and mirrored to commercial selectivity above the MLS of 20 cm

(Figures 3.10; 3.11). The historical survey selectivity for Gould was pre-specified to a lower length selectivity according to the results presented in Leeworthy (2007a) and following model tuning to improve the fit to the survey biomass estimates.

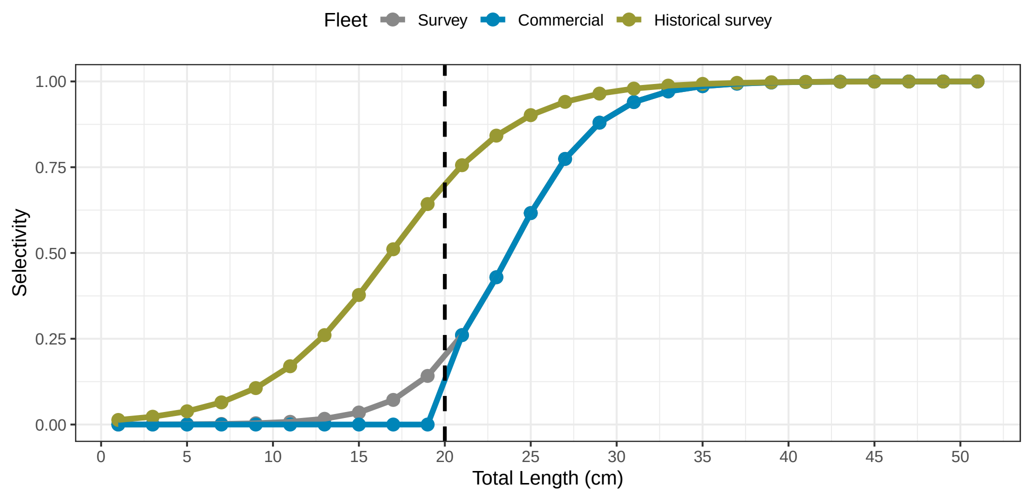

Figure 3.10: Estimated survey length selectivity and mirrored commercial selectivity for Gould. The black dashed line represents the minimum legal size of 20cm.

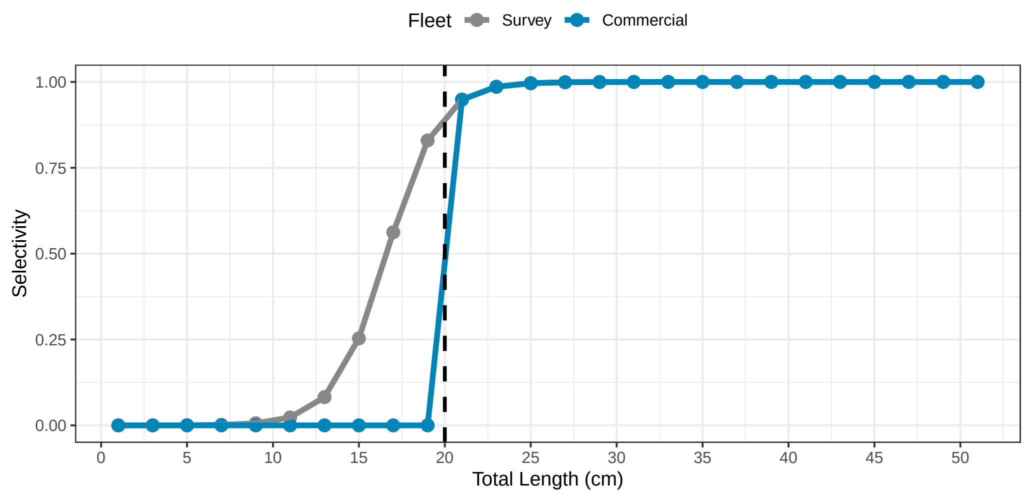

Figure 3.11: Estimated survey length selectivity and mirrored commercial selectivity for Bunker. The black dashed line represents the minimum legal size of 20cm.

3.2.4 Biomass

3.2.4.1 Gould stock

Fourteen model scenarios were run in Stock Synthesis for the gould stock, covering a range of modelling assumptions and sensitivity tests. The base case predicted stock biomass showed a gradual decline between 2000 and present and suggests the gould stock is currently the lowest it has ever been at a value of 72% unfished biomass. The relative spawning biomass was estimated to be between 51% and 101%, and most likely at 72%, of unfished biomass at the beginning of 2024 (Figure 3.12). The absolute spawning biomass trajectory indicates the most likely virgin spawning stock size was 2457 t and the most likely current spawning stock size is 1764 t (Figure 3.14).

Relative biomass trajectories for all Stock Synthesis sensitivity scenarios are presented in Figure 3.15. In general, all scenarios – aside from Scenario 8 – followed a similar trend to the base case scenario. Scenario 8, in which extra catch rate variance was estimated resulted in a biomass trend showing rapid depletion and recovery with a significant drop in the past 5 years.

The Stock Synthesis base case scenario relative biomass trend is compared to the DDUST base case scenario in Figure 3.16. Both models indicate similar depletion levels and the DDUST model results in larger uncertainty around the predicted trajectory.

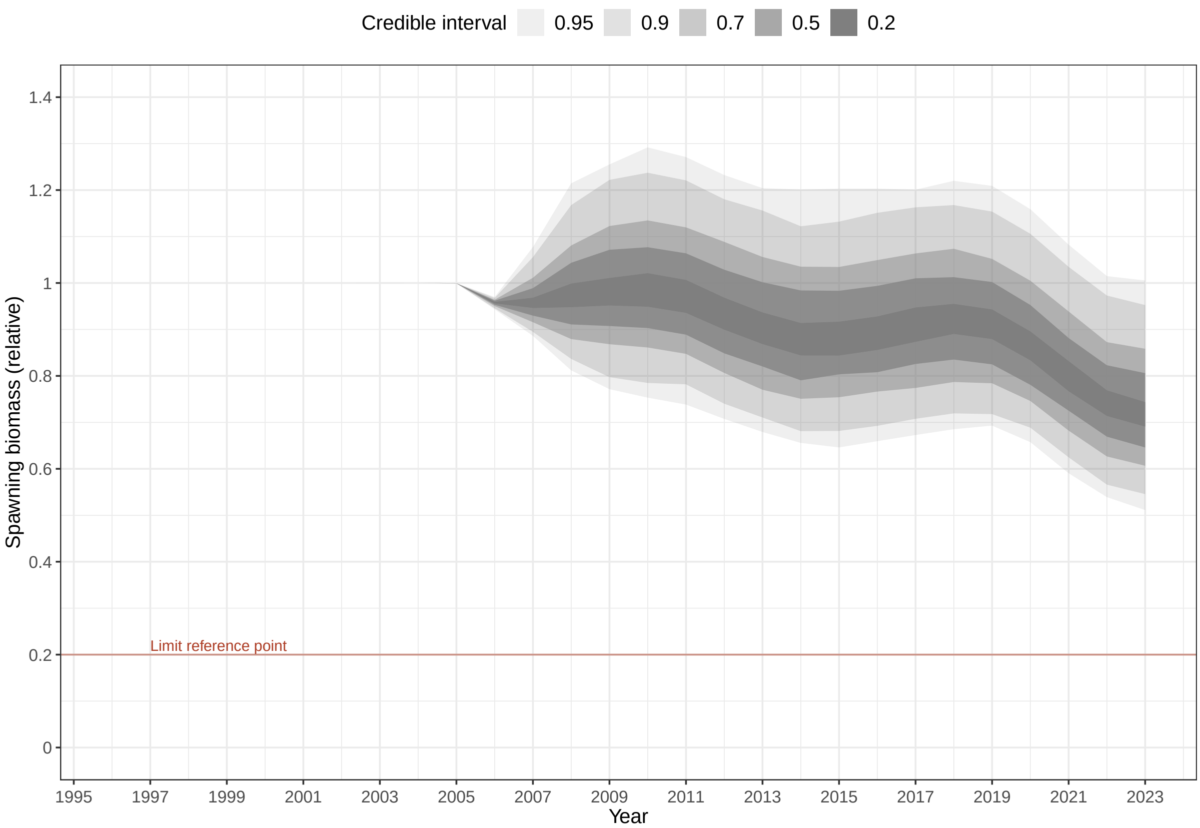

Figure 3.12: Estimated biomass trajectory relative to unfished from the base case Stock Synthesis model for the Gould stock, from 1996 to 2023.

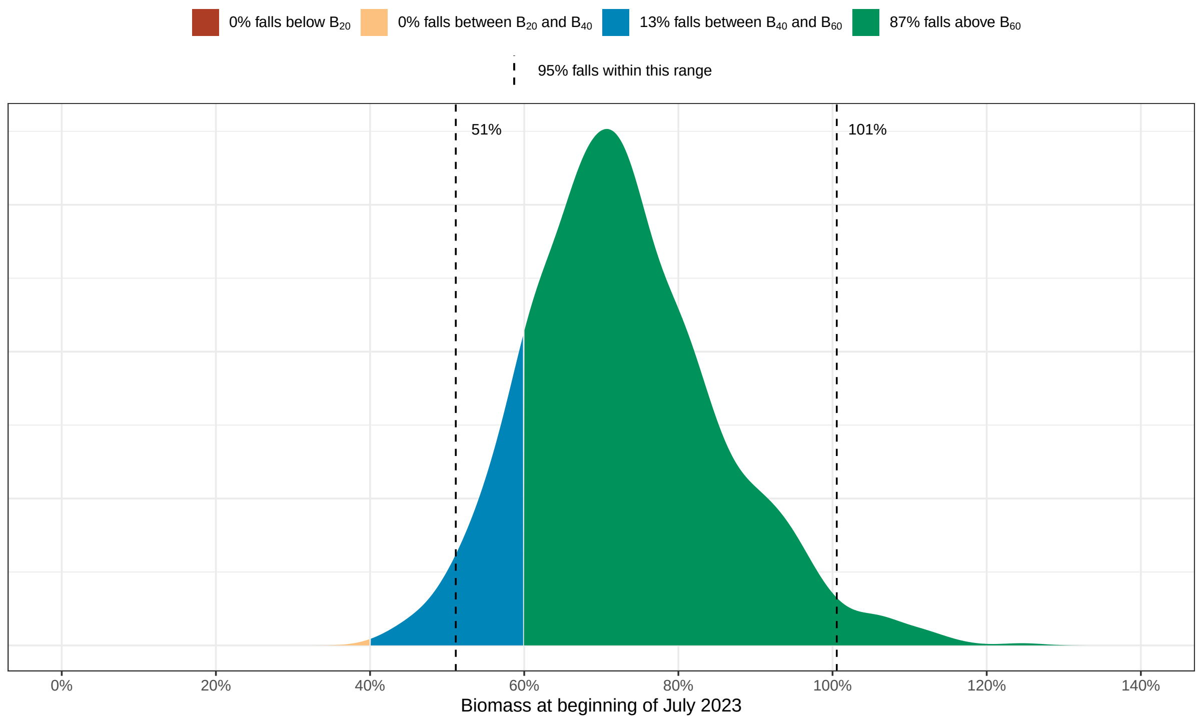

Figure 3.13: Probability distribution of the biomass ratio in 2023 for the base case Stock Synthesis model for the Gould stock with the credible interval and probability of biomass falling into the three categories indicated.

Table 3.3: Current and target indicators for the Queensland east coast burrowing blackfish Gould stock

Indicator	Value
Biomass ratio relative to unfished)	
Range (95% credible interval)	51–101%
Probability below 20%	0%
Probability between 20% and 40%	0%
Probability between 40% and 60%	13%
Probability above 60%	87%
Average five-year (2019 to 2023) retained commercial catch (boiled and frozen weight)	18 t

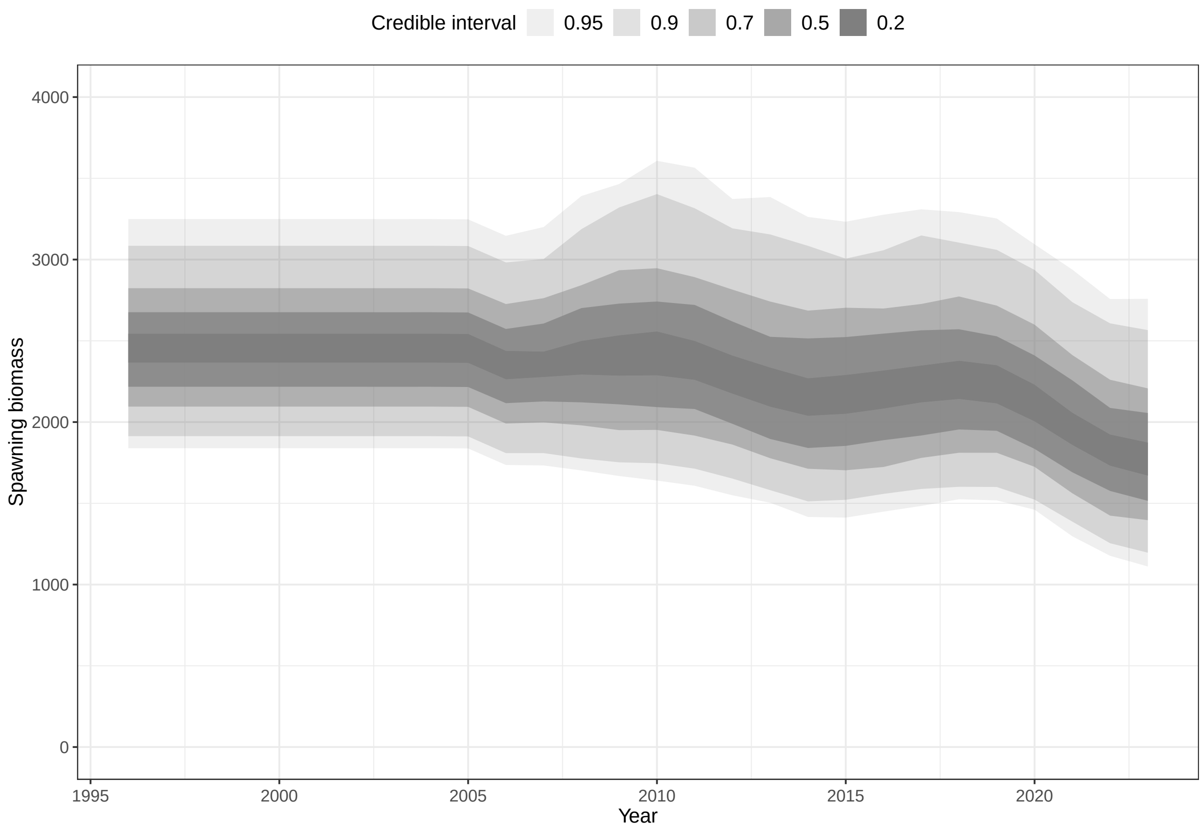

Figure 3.14: Estimated absolute spawning biomass trajectory from the base case Stock Synthesis model for the Gould stock, from 1996 to 2023.

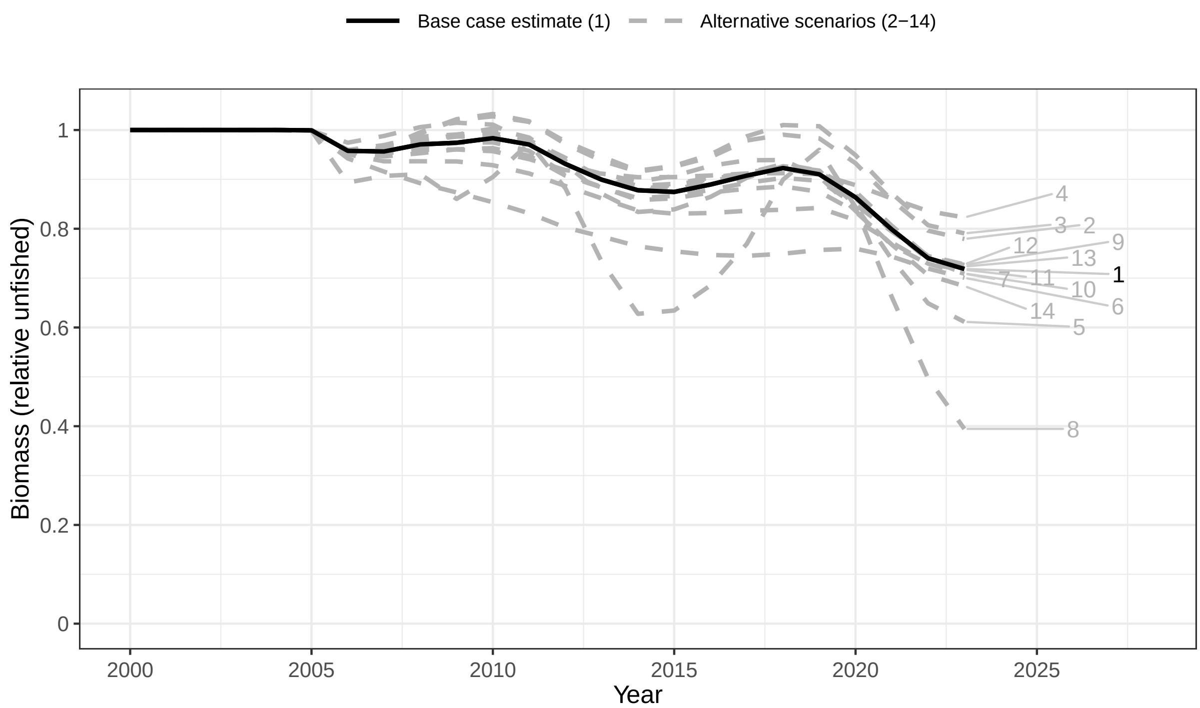

Figure 3.15: MCMC predicted biomass trajectory relative to unfished for the Gould stock, from 2000 to 2023 for all Stock Synthesis model scenarios.

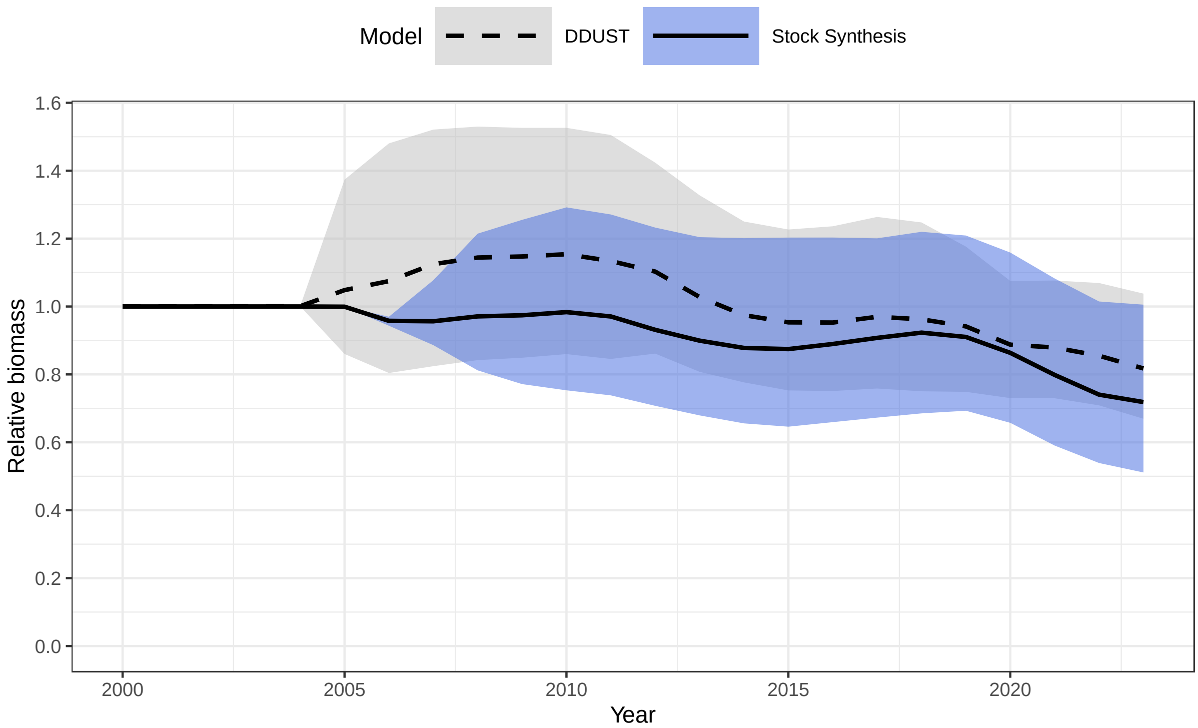

Figure 3.16: MCMC predicted biomass trajectory relative to unfished for the Gould stock, from 2000 to 2023 for the DDUST (grey shading and dashed black line) and Stock Synthesis (blue shading and solid black line) base case models. Note that the biomass presented for Stock Synthesis is spawning biomass while the biomass presented for DDUST is legal-size biomass.

3.2.4.2 Bunker stock

Fifteen model scenarios were run in Stock Synthesis for the bunker stock, covering a range of modelling assumptions and sensitivity tests. The base case predicted stock biomass shows little change in stock size between 1996 and 2023. The predicted biomass trajectory suggests the bunker stock reached its lowest point of 83% unfished biomass in 2022. The relative spawning biomass was estimated to be between 78% and 109%, and most likely at 92%, of unfished biomass at the beginning of 2024 (Figure 3.17). The absolute spawning biomass trajectory indicates the most likely virgin spawning stock size was 2390 t and the most likely current spawning stock size is 2197 t (Figure 3.19).

Relative biomass trajectories for all Stock Synthesis sensitivity scenarios are presented in Figure 3.20. In general, all scenarios followed a similar trend to the base case scenario.

The Stock Synthesis base case scenario relative biomass trend is compared to the DDUST base case scenario in Figure 3.21. Both models indicate similar depletion levels and the DDUST model results in larger uncertainty around the predicted trajectory.

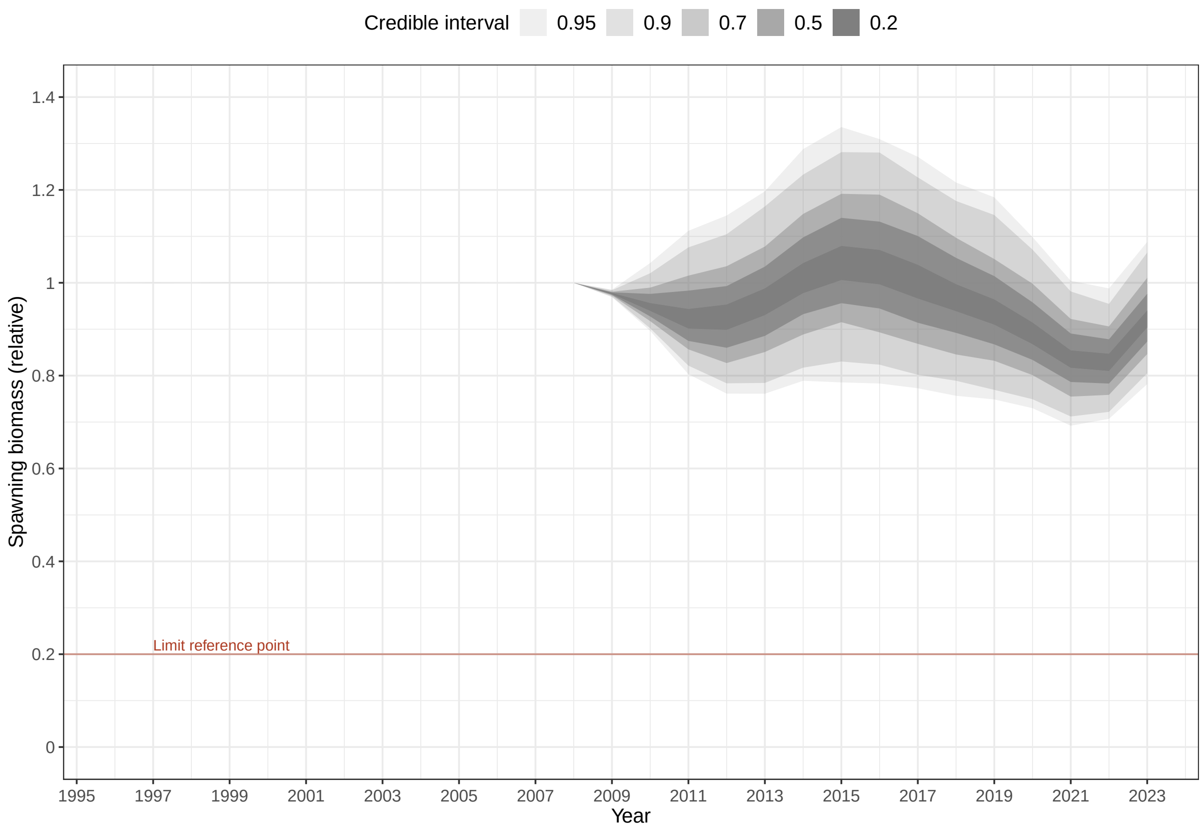

Figure 3.17: Estimated biomass trajectory relative to unfished from the base case Stock Synthesis model for the Bunker stock, from 1996 to 2023.

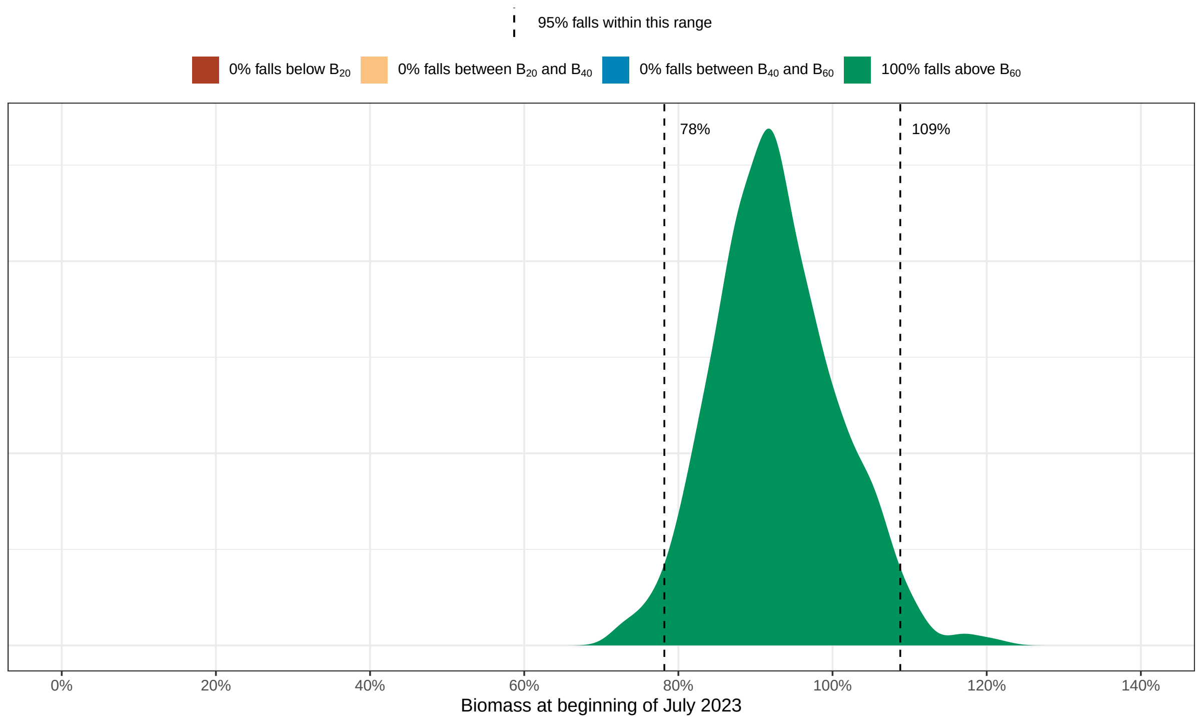

Figure 3.18: Probability distribution of the biomass ratio in 2023 for the base case Stock Synthesis model for the Bunker stock with the credible interval and probability of biomass falling into the the category indicated.

Table 3.4: Current and target indicators for the Queensland east coast burrowing blackfish Bunker stock

Indicator	Value
Biomass ratio relative to unfished)	
Range (95% credible interval)	78–109%
Probability below 20%	0%
Probability between 20% and 40%	0%
Probability between 40% and 60%	13%
Probability above 60%	87%
Average five-year (2019 to 2023) retained commercial catch (boiled and frozen weight)	24 t

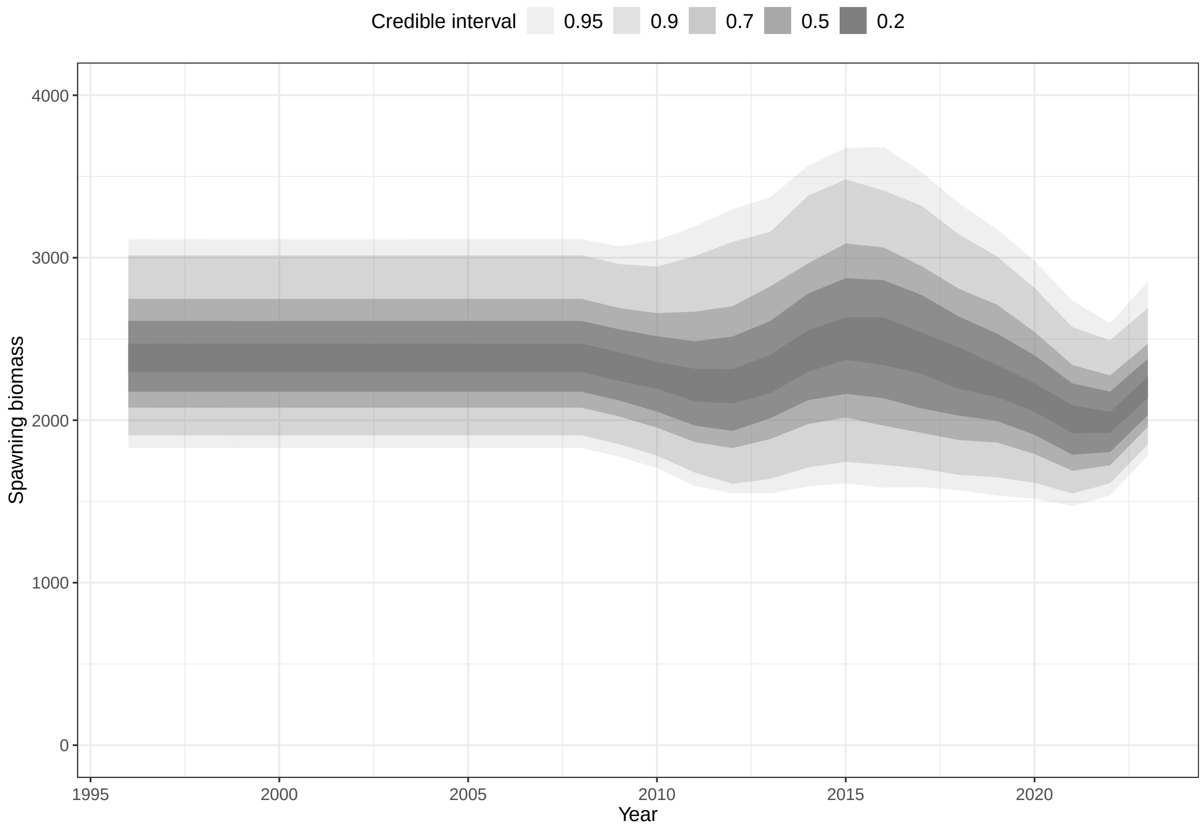

Figure 3.19: Estimated absolute spawning biomass trajectory from the base case Stock Synthesis model for the Bunker stock, from 1996 to 2023.

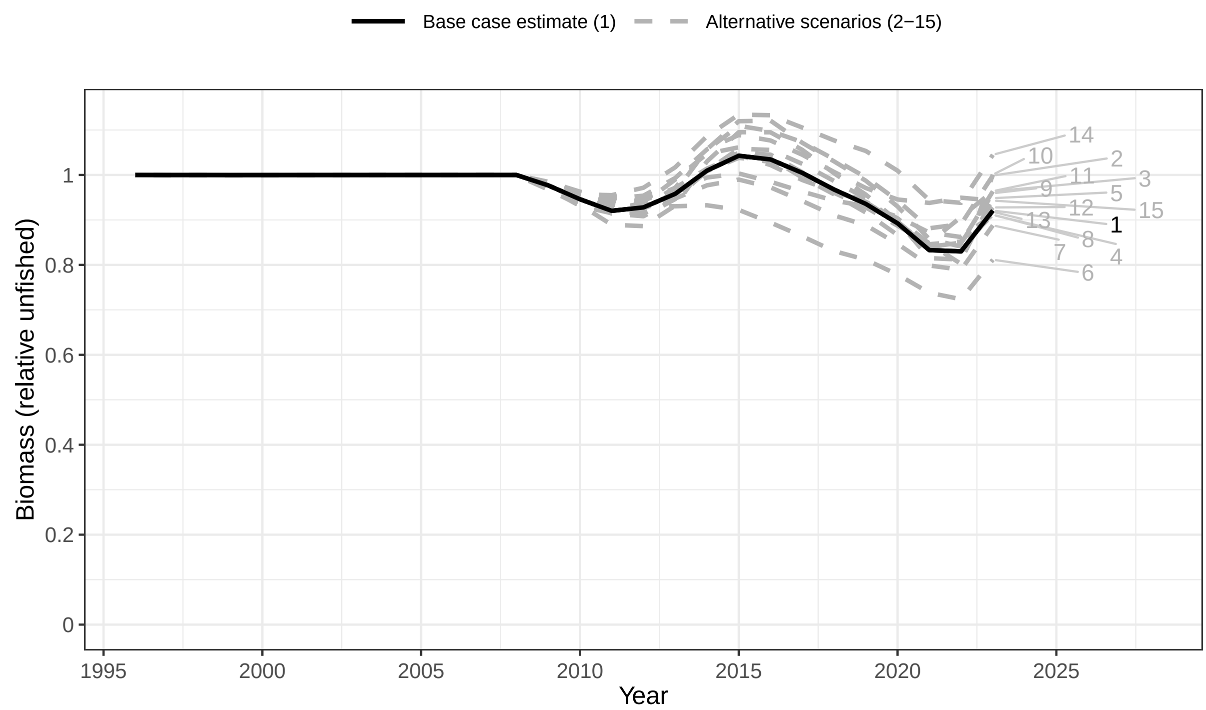

Figure 3.20: MCMC predicted biomass trajectory relative to unfished for the Bunker stock, from 1996 to 2023 for all Stock Synthesis model scenarios.

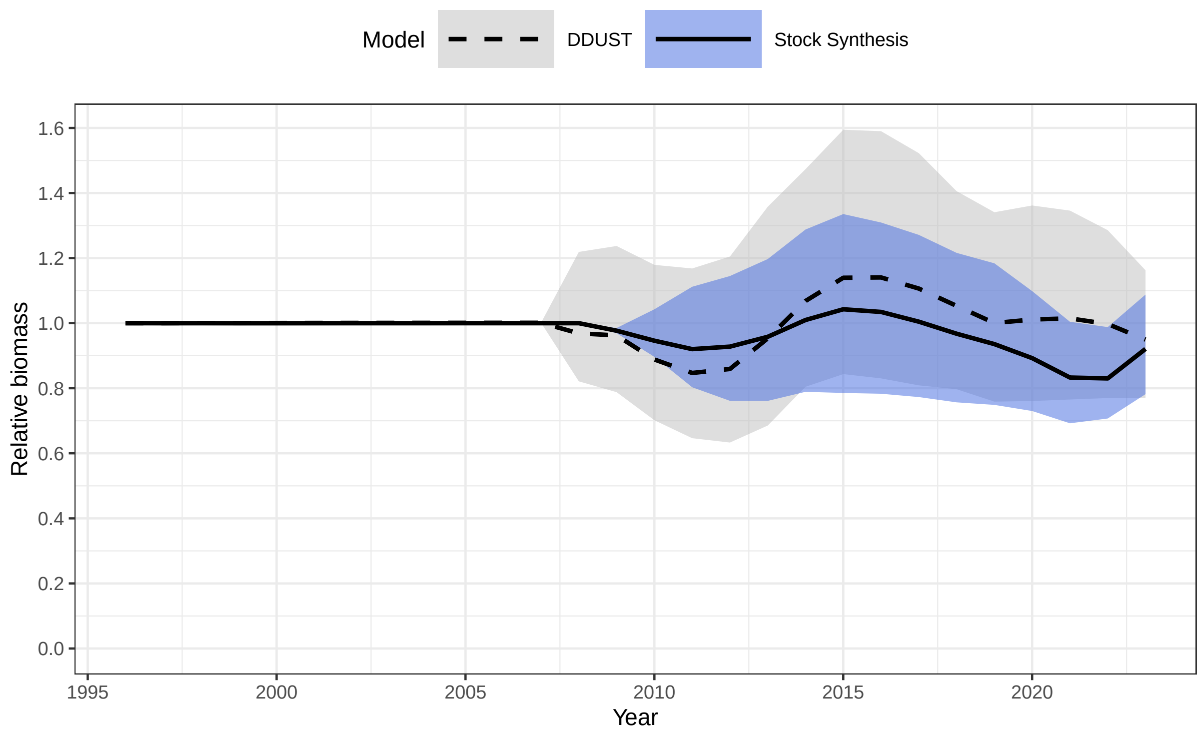

Figure 3.21: MCMC predicted biomass trajectory relative to unfished for the Bunker stock, from 1996 to 2023 for the DDUST (grey shading and dashed black line) and Stock Synthesis (blue shading and solid black line) base case models. Note that the biomass presented for Stock Synthesis is spawning biomass while the biomass presented for DDUST is legal-size biomass.

4 Discussion

4.1 Stock status

This was the first assessment of east coast burrowing blackfish by Fisheries Queensland. The base case models (Stock Synthesis and DDUST) demonstrated that stocks in the Gould and Bunker BBZ are above 60% of unfished spawning biomass and have not been reduced below this level since the commencement of the fishery. Recent 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 in the early 2000's. Correspondingly, each of the assessment models support this. Based on the Stock Synthesis model results the unfished levels of biomass were 72% for Gould, and 92% for Bunker. The DDUST model results were similar to those of Stock Synthesis for each stock.

The Lizard stock recent biomass survey results demonstrated ongoing stock declines in the absence of fishing (Koopman et al. 2024). Further details about the status of Lizard BBZ are in Appendix A. Similar declines were not detected for Gould and Bunker. However, the implications of the Lizard stock decline are discussed for the ongoing monitoring and assessment of these BBZ in Appendix A.

4.2 Performance of the population models

Two different stock assessment models were applied to burrowing blackfish stocks to account for the data-limited nature of this assessment. Routine collection of lengths, ages and weights has not been undertaken for the fishery and the only data available for both stocks were catch, catch rates, and estimates of biomass and length composition from recent surveys (Koopman et al. 2019; Koopman et al. 2023). Three additional surveys were conducted for Gould from 2004 to 2009 with the first of these included in this assessment (Leeworthy 2007a). The subsequent two surveys could not be included as low density sites were not resampled, preventing accurate biomasses from being estimated. A similar survey for Bunker could not be included as it covered a different area to the recent survey (Leeworthy 2010; Koopman et al. 2023).

The Stock Synthesis model makes full use of all these data, allowing selectivity and the MLS to be accounted for in the stock assessment process. However, Stock Synthesis requires biological information on growth that is unknown for burrowing blackfish. Alternatively, DDUST requires minimal 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 stocks and their results were compared. Both models performed adequately across most scenarios for both stocks, and Stock Synthesis was 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, the DDUST model did not provide contrary conclusions. Sensitivity analyses focusing on growth also did not measurably change the Stock Synthesis results. Therefore, while assuming growth parameters was not ideal, and their acquisition should be a focus of future research, Stock Synthesis was able to adequately model the east coast burrowing blackfish stocks.

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 can 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 both stocks 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. Fourteen scenarios were applied for the Gould stock with a fifteenth applied for Bunker. For Bunker, all scenarios performed very similarly and for Gould, most provided results that were not consequentially different from the base case model.

The three scenarios for Gould that were different to the base case were the scenario with a higher σ_R estimate of 0.4 (Scenario 5), the scenario with a low M estimate of 0.3 yr^{-1} (Scenario 6) and where no additional variance was estimated for catch rate (Scenario 8). Scenario 6 presented a more pessimistic relative biomass series, although this remained above 60% unfished biomass in 2023. However, the model fits to biomass, catch rates and length compositions were poorer than the base case model. Scenarios 5 and 8 provided a series of relative biomass with implausible fluctuations, sometimes increasing far above 100% of unfished biomass. This was caused by overfitting to the catch rate indices and subsequent estimation of large recruitment deviations to permit this. These scenarios provided the poorest fits to biomass and length compositions and were also dismissed.

4.2.2 DDUST

The DDUST base case models performed best for both stocks in terms of model fit and plausibility of results (relative and absolute biomass, recruitment deviations and *F*). Most scenario 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. Good fits to legal-size biomass were achieved for Bunker although Gould did not provide a predicted legal-size biomass that was within the 95% confidence intervals of the 2020 survey estimate. This occurred as the Gould legal-size biomass estimate from the survey had larger uncertainty than other recent surveys (Koopman et al. 2019; Koopman et al. 2022; Koopman et al. 2023). This was overcome by Stock Synthesis but not by DDUST.

Scenarios 1 to 10 applied to Stock Synthesis were also applied to DDUST (Scenarios 11 to 15 were not applicable) and yielded similar results with the same conclusions for stock status. For Gould, Scenario 6 (M = 0.3) provided lower estimates of relative biomass than the base case mode. For both Gould and Bunker, Scenarios 5 and 8 provided implausible relative biomass fluctuations with poorer fits to the data than the base case models for each stock.

4.2.3 Natural Mortality (*M*) pre-specification

Scenario 6, which used a lower value of *M*, was the sole sensitivity test requiring additional consideration, with consistent results occurring across stocks and models. 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 burrowing blackfish life history to inform estimates of *M*. The pre-specified value of $M = 0.73\ yr^{-1}$ was sourced from the MSE conducted by Skewes et al. (2014) and was sensitivity tested through additional scenarios. A lower value of $M = 0.3\ yr^{-1}$ yielded a different biomass trajectory but had little support in comparison to the base case models. For Gould, the fit to biomass was worse for both models as well as the fit to length compositions for Stock Synthesis. For Bunker, the fit to biomass was worse for DDUST while the fit to length composition was worse for Stock Synthesis. The likelihood profile for *M* for Gould showed increased model support for higher values for DDUST, while there was no significant difference across values for Stock Synthesis (i.e., the log-likelihood differences were less than two). For Bunker, likelihood profiles for both models supported a higher *M*. Therefore, while a value of $M = 0.73\ yr^{-1}$ may be considered high, there is no support in 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

The BBZ were treated as independent stocks in this assessment which aligns with an MSC Type B stock structure classification that recommends management and assessments occur at a local scale. There are many examples of sea cucumber populations where localised depletion has easily occurred, and recovery rates have been slow (Friedman et al. 2011; Uthicke et al. 2004). This suggests that reasonably segregated sub populations of sea cucumbers can exist when a species has a large range. Burrowing blackfish span the GBR and the Torres Strait but occur in high densities within discrete regions, hence the formation of BBZ. While there is recent evidence of GBR-wide genetic interconnectivity (Williamson et al. in prep), the large geographic distances between zones (more than 500 km) increase the likelihood that a reasonable degree of self-seeding occurs. 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), which aligns with the recent results from Williamson et al. in prep. While ideal, this is not possible with the data and information available. Treating these BBZ as independent stocks makes best use of the available information but the opportunity to consider meta-population dynamics has obvious merit and justifies future research attention.

4.3.2 Marine park zoning

Burrowing blackfish catches have occurred since logbook records began in 1996 but large catches associated with BBZ did not occur until 2004 when the GBRMP was rezoned. Therefore, no catches have historically occurred within areas that are now closed to fishing. As a result, 37% of the GBRMP has never been fished for burrowing blackfish and little to no information is available from these areas to be included in the stock assessment. Some limited sampling occurred in green zones in the corresponding biomass surveys (Koopman et al. 2019; Koopman et al. 2022; Koopman et al. 2023), but this alone is insufficient to model areas closed to fishing. This assessment has therefore only modelled the portion of burrowing blackfish 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 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 burrowing blackfish 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). However, no other species can be co-caught within the the BBZ during burrowing blackfish fishing events. Therefore, impacts of multi-species fishing are not problematic for burrowing blackfish catch rates.

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 burrowing blackfish catches can be more related to fishery decision making than stock status, placing greater importance on stock assessments.

4.4 Recommendations

4.4.1 Research and monitoring

4.4.1.1 Data

Life history and biological information is often missing for sea cucumber species (Friedman et al. 2011; Purcell et al. 2013), although the information for burrowing blackfish is especially poor (Wolfe et al. 2022). This was overcome in this assessment by applying multiple 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 as a result information on growth should be collected as a priority.

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 trialed in Abalone fisheries and is now in operation in several Australian jurisdictions (Mundy 2012). However, they can 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.

Lastly, a conversion factor is not available for the main burrowing blackfish product weight form – 'boiled and frozen weight.' As a result, a salted weight conversion factor sourced from the Torres Strait fishery

(Murphy et al. 2021) was used in this assessment. Obtaining a correct and accurate conversion factor should be a priority for the QSCF as a salted weight conversion factor is likely to be conservative.

4.4.1.2 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 these surveys, not only for these burrowing blackfish assessments, but also for any other sea cucumber species in the QSCF that may be assessed in the future. Currently, selectivity is estimated from a single year of length frequency data available from recent surveys (Koopman et al. 2019; Koopman et al. 2023) 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. Time series of biomass estimates provide empirical estimates of population productivity when combined with retained catch over the same period. This information has been invaluable for Lizard and Gould and additional surveys would similarly benefit Bunker. Multiple surveys allow the biomass trajectory between surveys to be better quantified as the model can consider the relative impact of catch (removals) and recruitment (additions) on the population. 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, additional surveys would provide ongoing value to the assessments.

4.4.2 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. Both burrowing blackfish stocks assessed here were above this level in 2023 and have not declined below 60% during their exploitation history.

4.4.3 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.
- **Including populations outside of BBZ.** The current assessment has only modelled burrowing blackfish populations within two of the three BBZ. However, other catches of burrowing blackfish occur outside of these zones in multi-species fishing activities managed through the RHA. These populations have not yet been assessed as survey estimates are not available for these areas.

However, consideration of these populations in future assessments would be beneficial even if the results are uncertain.

- **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 burrowing blackfish, 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, for burrowing blackfish this would require greater information on length-at-age before it could be appropriately implemented.

4.5 Conclusions

This assessment was commissioned to establish the status of Queensland's east coast burrowing blackfish stock and inform the management of the East Coast Sea Cucumber Fishery. This assessment also addresses parts a) and b) of WTO condition 7 "The Queensland Department of Agriculture and Fisheries must:

a) Ensure data from fishery independent surveys of Burrowing Blackfish at the Lizard, Gould and Bunker Reef Burrowing Blackfish Zones are representative of the fishery and used to inform a stock assessment for the species.

b) Undertake and publish the stock assessment for Burrowing Blackfish. The stock assessment must be independently peer reviewed and must be completed by 30 May 2024."

The converged scenarios suggested current biomass (compared to unfished levels) for the Gould stock is 72 (51–101%), and for the Bunker stock is 92% (78–109%). Some recommendations for future work have been made.

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Appendix A Lizard BBZ population

The Lizard stock assessment modelling process failed to reconcile fishing pressure with the biomass decline observed through survey estimates of absolute biomass. Biomass surveys of Lizard BBZ have been undertaken in 2005, 2022 and 2024 (Leeworthy 2007a; Koopman et al. 2022; Koopman et al. 2024). Leeworthy (2007a) used different methodologies and covered different areas, so the survey required post-stratification for comparability with the recent the biomass estimates. For 2005, the post-stratified biomass for Lizard was estimated at 10,813 t live weight, indicating an 84% stock decline when considered with the 1,767 t biomass estimate from 2022 (Koopman et al. 2022). However, during this period catches only summed to 2,981 t live weight, indicating that such a decline could not be explained by fishing alone. The QSCF took the cautious measure of voluntarily closing this BBZ and scheduling another survey in two years' time so that the population change without fishing could be tracked. In March 2024, an additional survey replicated the 2022 survey to estimate the change in biomass during the fishery's voluntary closure. The biomass estimated by this survey was 935 t live weight equating to a 57% stock decline during a two year period with no fishing.

Consideration of these three biomass estimates (2005, 2022 and 2024) and corresponding catches indicated that a substantial stock decline has occurred, but was not wholly driven by fishing. QSCF catches would have produced light fishing pressure of less than 6% since 2005. Instead, decreasing population productivity through increased M and/or decreased recruitment is probable. The drivers of this are unclear but there are two initial possibilities. Firstly, as highlighted within the independent review (Buckworth et al. 2024), it is possible that burrowing blackfish stocks in each of the three BBZ are dynamic populations that have not always existed at large densities in these locations. Instead, they may be the result of recent (on a decadal scale) recruitment events where oceanographic conditions delivered larvae to these patches of optimal burrowing blackfish habitat. Subsequent existence of these populations hinged on their ability to self replenish, and it is possible that the Lizard BBZ does not have this ability. This situation would result in a population that would erode through time as mortality outpaces the low levels of self seeding that occur. Such a possibility was discussed during the independent review, without knowledge of this situation, and a future research recommendation of the review was to consider how dynamic stocks such as these could be best managed (Buckworth et al. 2024). The second possibility is that the Lizard BBZ was an established stock that had the ability to self seed and has done so for generations. However, a regime shift has now reduced its productivity leading to population declines. In 2016, Lizard Island was impacted by Tropical Cyclone Ita as well as several coral bleaching events in 2016, 2017, 2020 and 2022. A changing climate and environmental impacts are potential causes of the population decline, although this would require additional research to be confirmed.

The implications of the Lizard stock decline must also be considered for Gould and Bunker. If these burrowing blackfish stocks are dynamic, and may change through time independent of fishing pressure, then this must be considered in a monitoring framework. The stock decline that occurred for Lizard was not apparent in catch rate analyses, indicating that even with standardisation, catch rates may be problematic for inferring stock status and population trends. This was already recognised in this report, where catch rates were included in the models but with additional variance being estimated. This essentially down-weights these data and places priority on fitting to biomass estimates and length compositions. Of the two stocks assessed here, far more confidence can be placed on the results for Gould where two surveys bookend the fishery's time series (Leeworthy 2007a; Koopman et al. 2019).

These indicate that changes in stock size are relatable to fishing pressure and therefore population productivity has not changed substantially through time as it has for Lizard. Only one survey is available for Bunker, therefore there is more reliance on catch rates than there is for Gould. Therefore, this stock would benefit from future surveys that track population changes through time against the corresponding catches. This would demonstrate that the populations dynamics are more similar to Gould than they are to Lizard.

Appendix B Model inputs

B.1 Abundance indices

B.1.1 Catch rate standardisation diagnostics

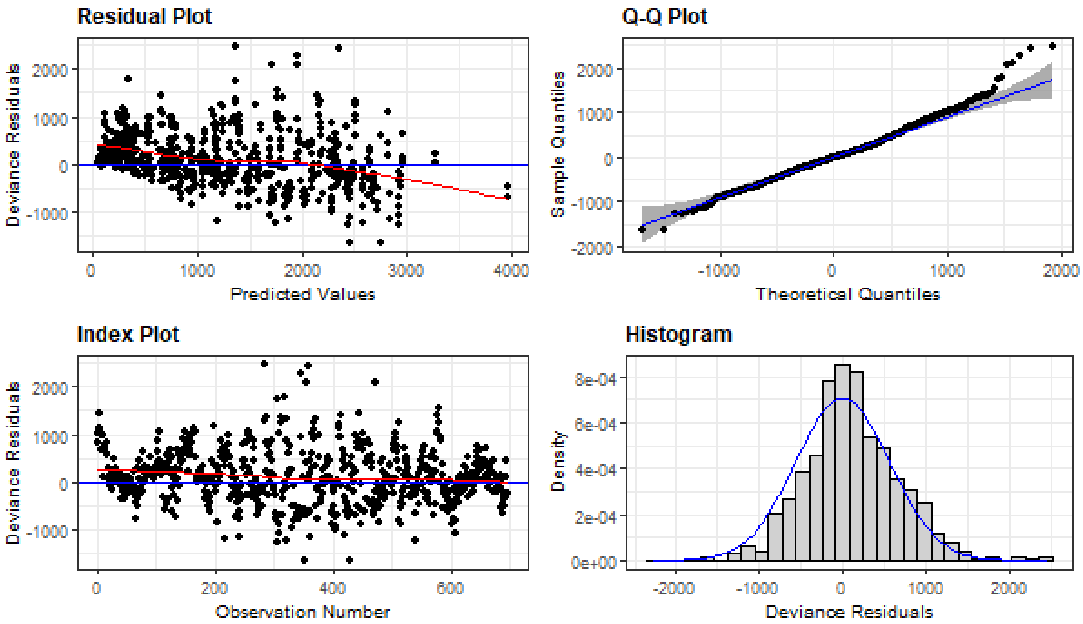


Figure B.1: Gould catch rate diagnostic plots.

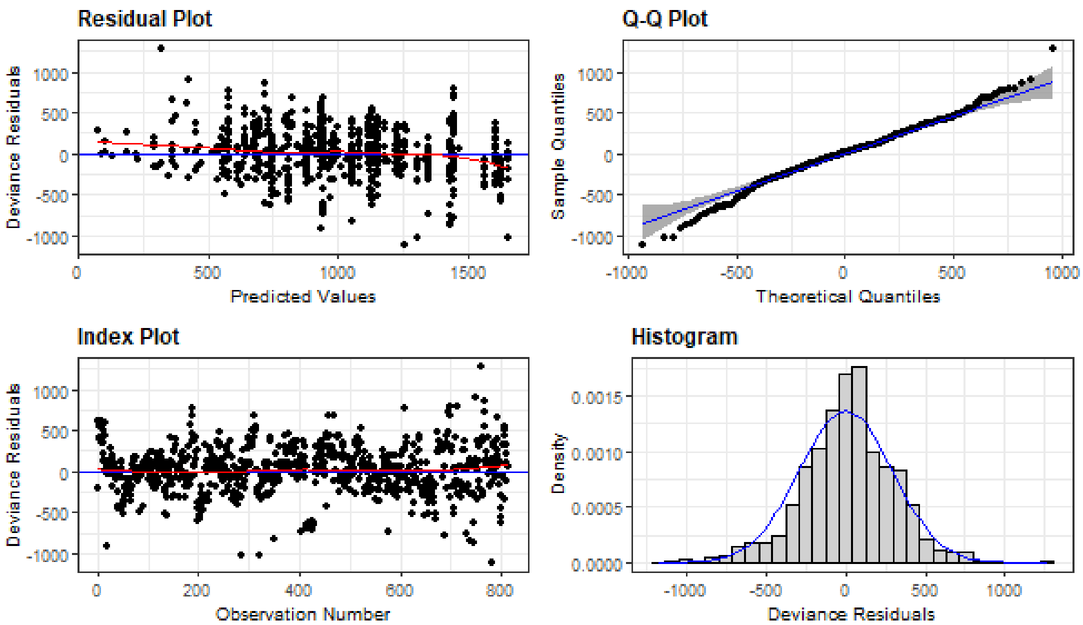


Figure B.2: Bunker catch rate diagnostic plots.

B.2 Biological data

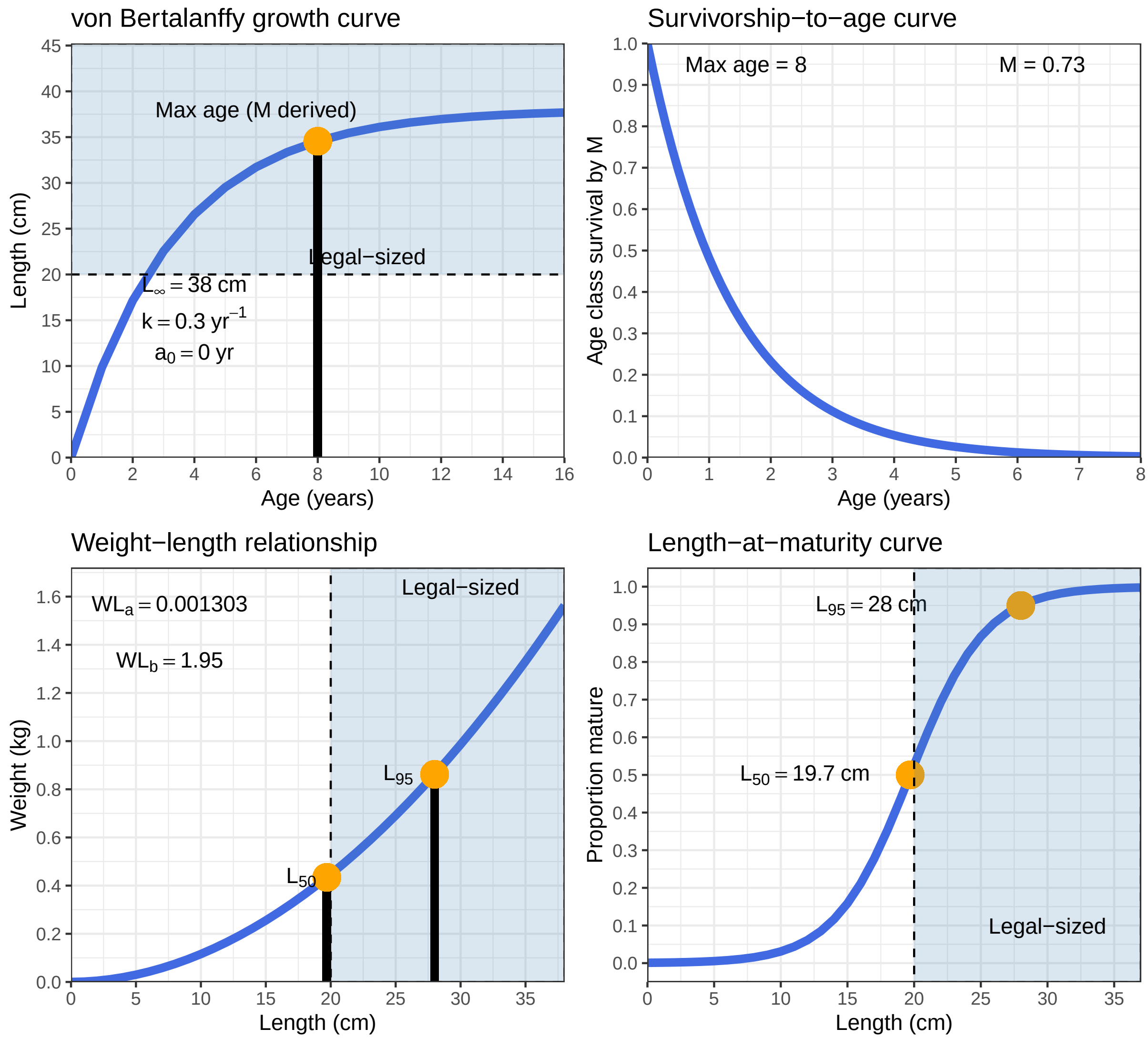


Figure B.3: Life history parameters for burrowing blackfish used in the stock assessment models.

Appendix C 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.

C.1 Abundance indices

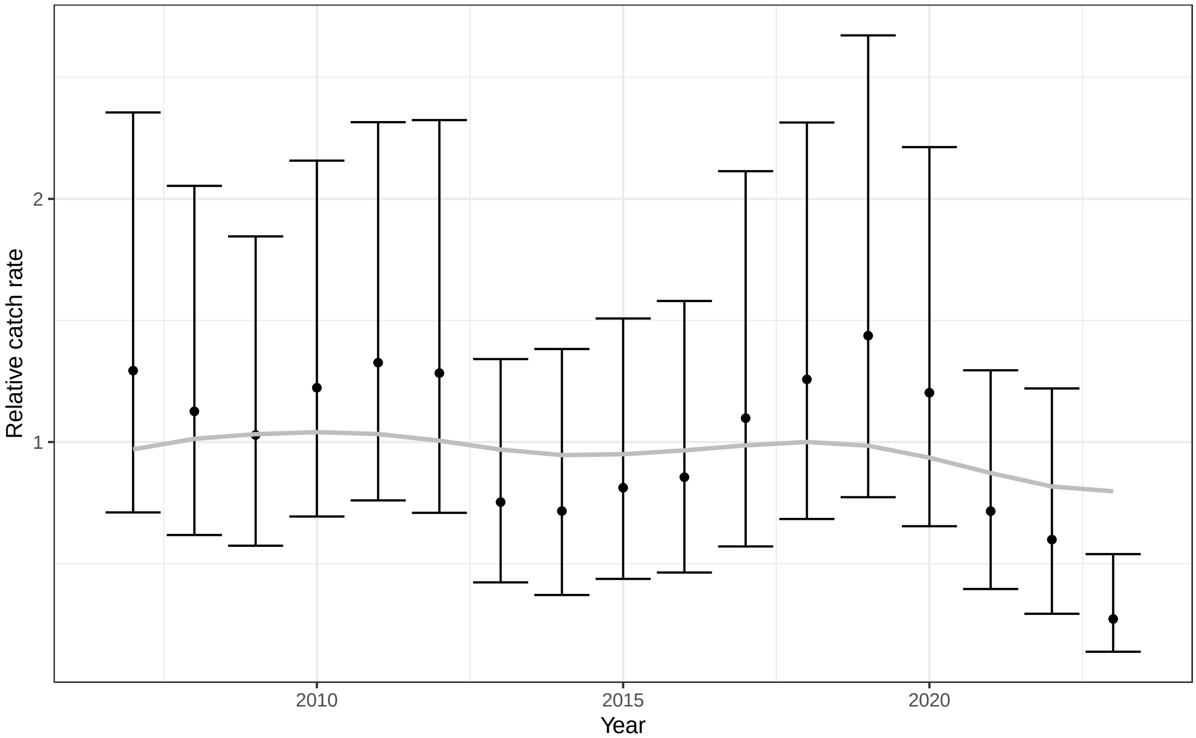


Figure C.1: Stock Synthesis base case model MLE estimates (grey line) of commercial catch rates for the Gould stock, from 2007 to 2023. Points and error bars represent the standardised catch rate and error input to the model, relative to the mean.

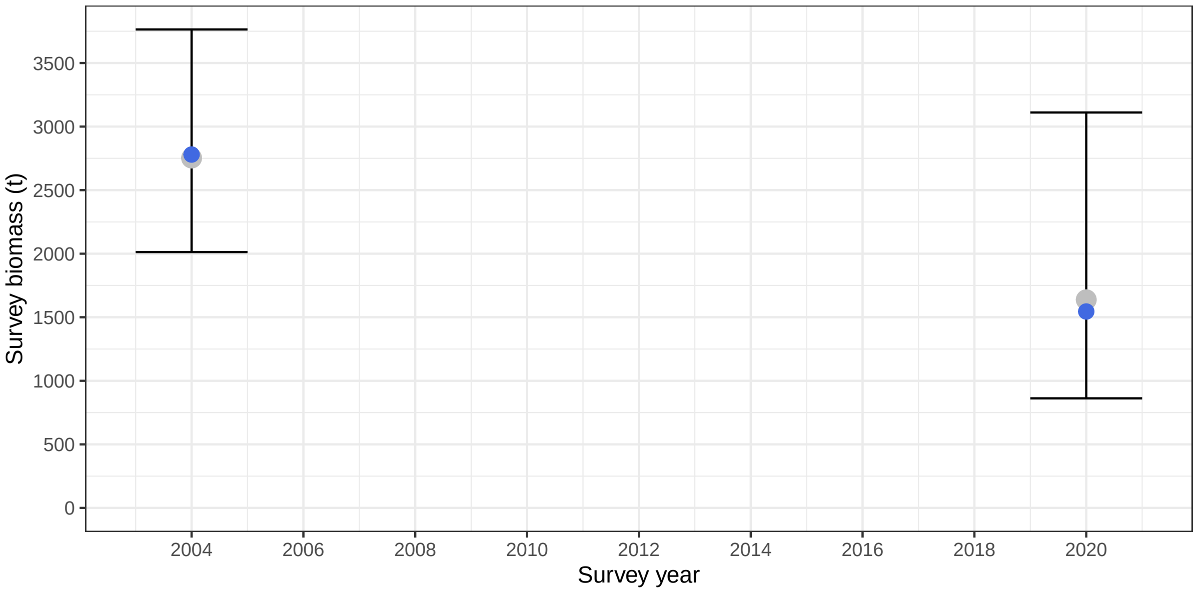


Figure C.2: Stock Synthesis model fits (blue dot) to survey estimated biomass (grey point with black error bars indicating the 95 percent CI of the estimate) for the Gould stock in 2004 and 2020.

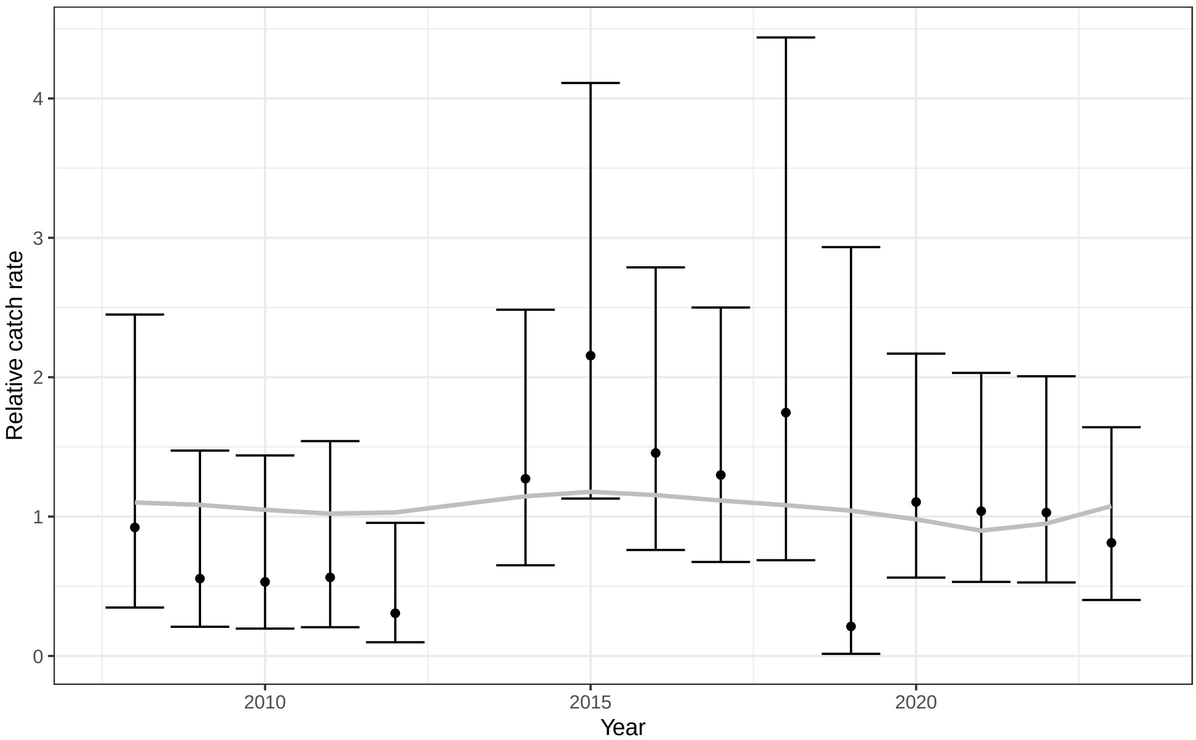


Figure C.3: Stock Synthesis base case model MLE estimates (grey line) of commercial catch rates for the Bunker stock, from 2007 to 2023. Points and error bars represent the standardised catch rate and error input to the model, relative to the mean.

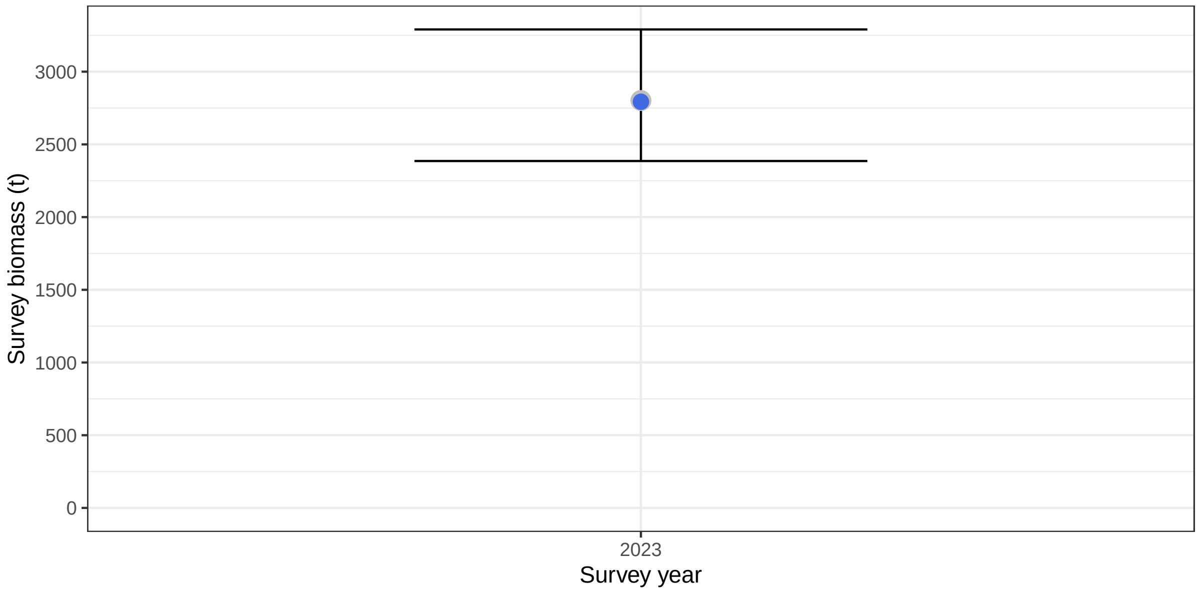


Figure C.4: Stock Synthesis model fit (blue dot) to survey estimated biomass (grey point with black error bars indicating the 95 percent CI of the estimate) for the Bunker stock.

C.2 Length composition

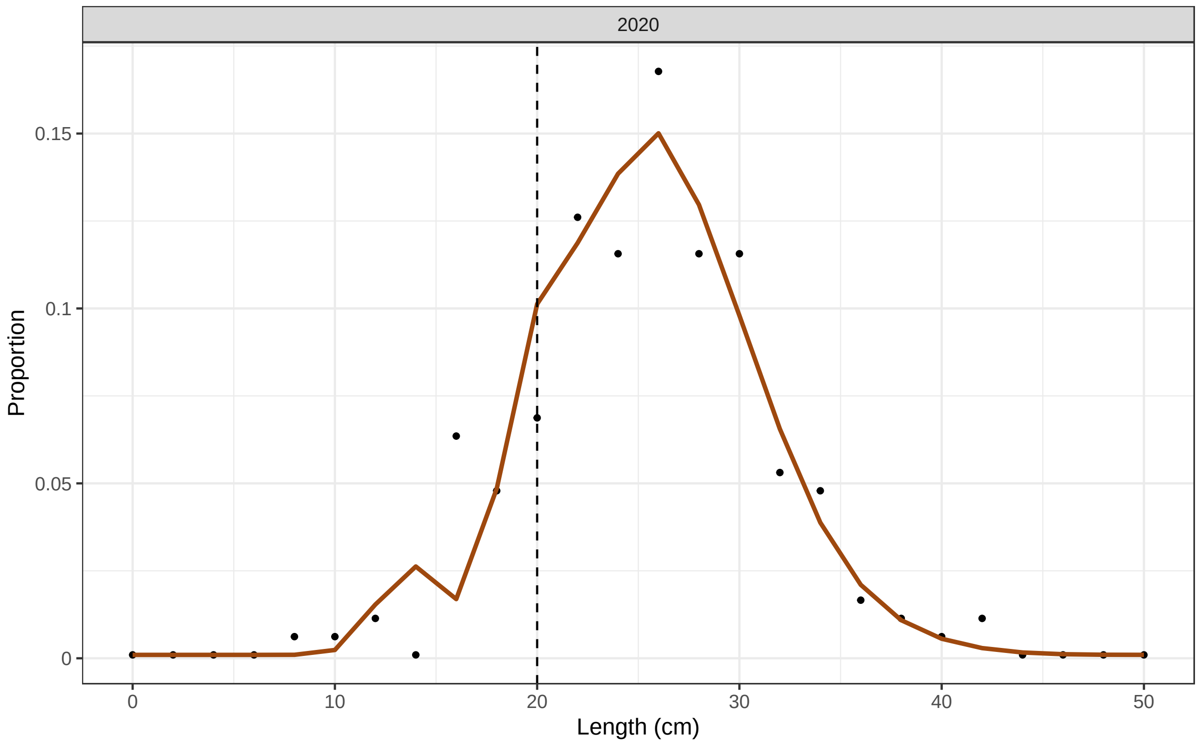


Figure C.5: Stock Synthesis model fits (brown line) to length structures for the 2020 survey for the Gould stock. The dashed vertical line indicates the MLS of 20 cm.

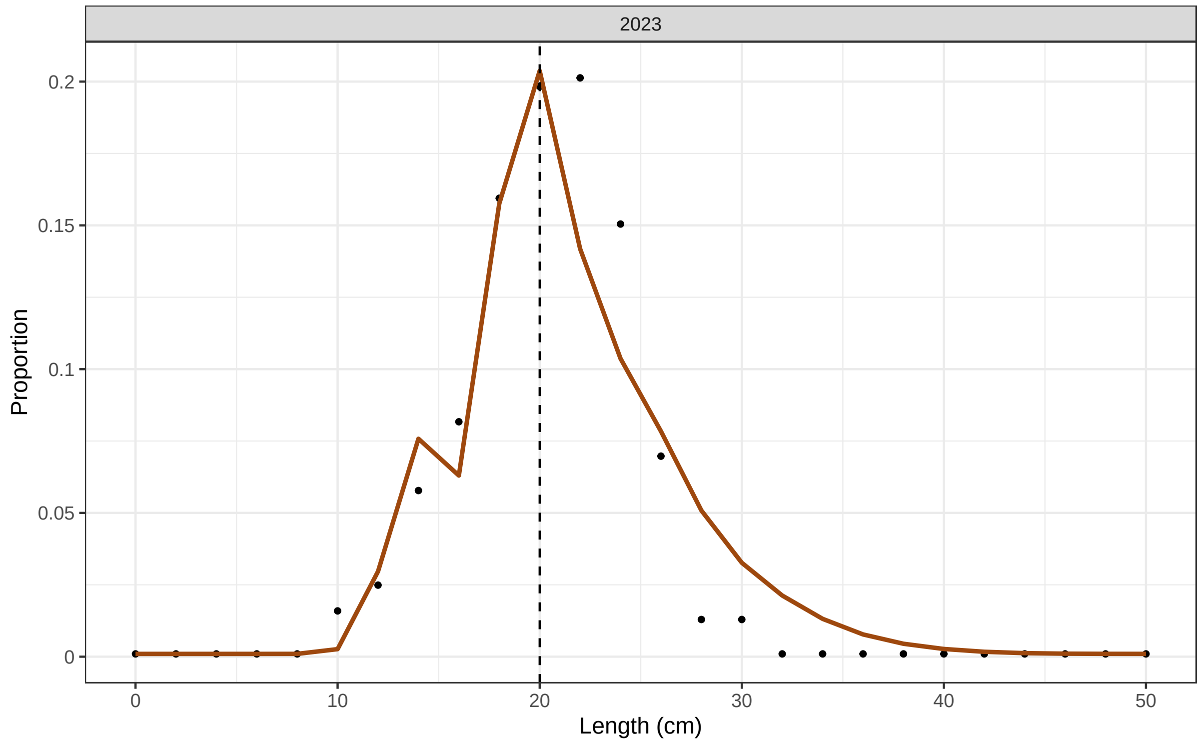


Figure C.6: Stock Synthesis model fits (brown line) to length structures for the 2023 survey for the Bunker stock. The dashed vertical line indicates the MLS of 20 cm.

C.3 Stock-recruitment curve

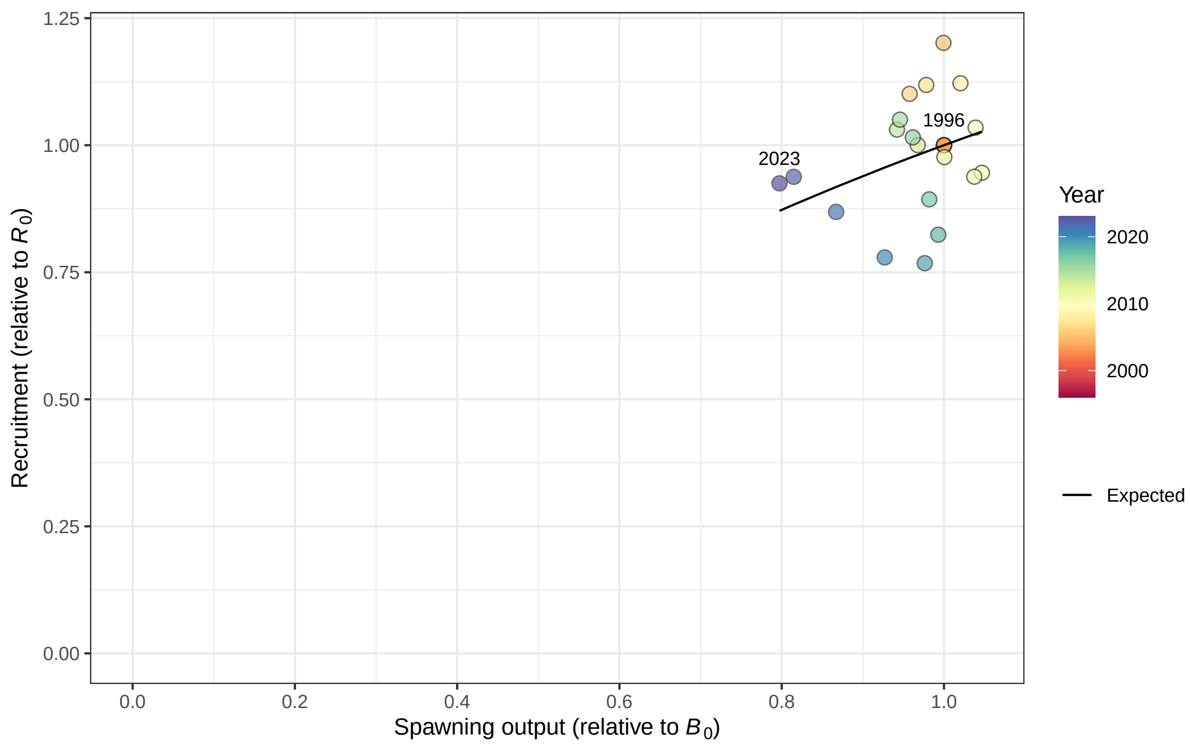


Figure C.7: Stock-recruitment curve estimated via Stock Synthesis MLE for the Gould stock. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

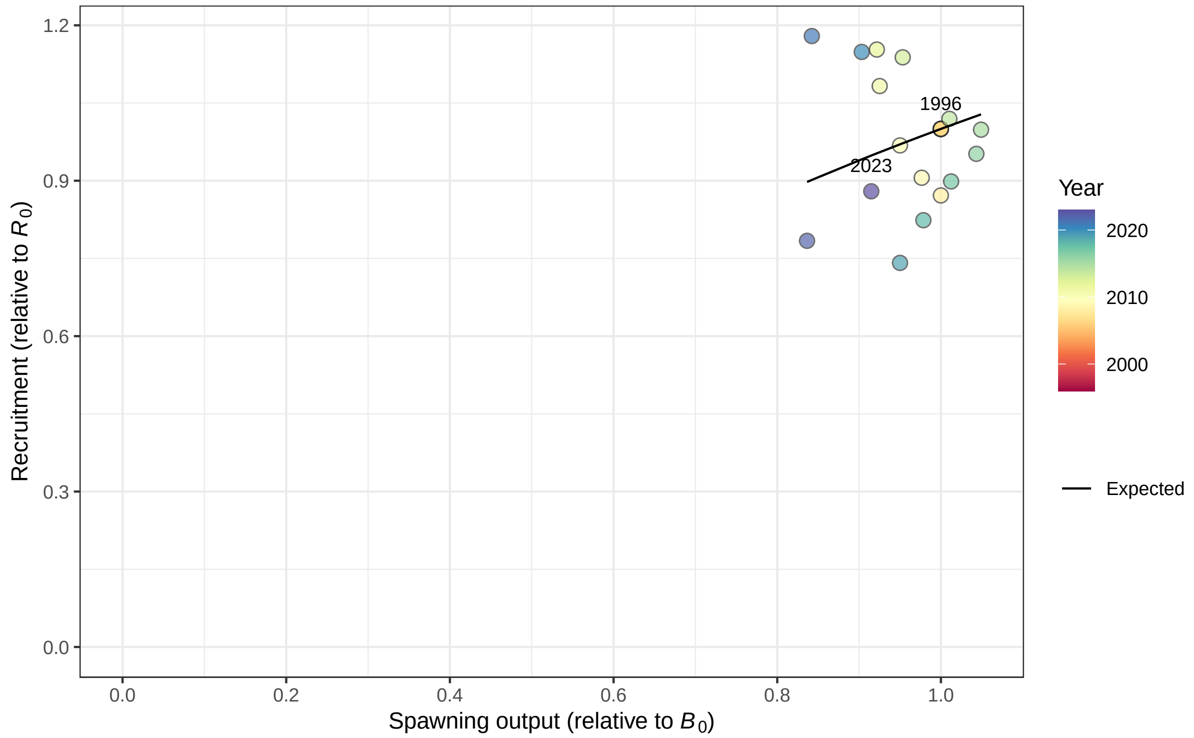


Figure C.8: Stock-recruitment curve estimated via Stock Synthesis MLE for the Bunker stock. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

C.4 Recruitment deviations

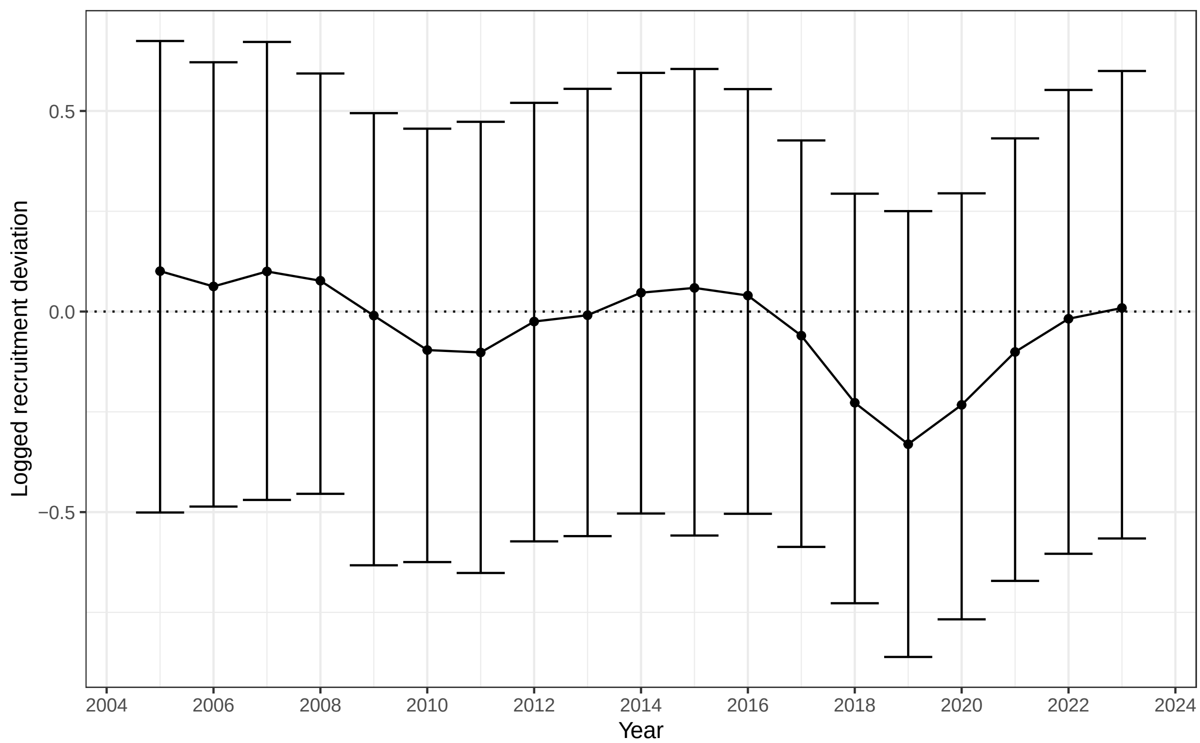


Figure C.9: Recruitment deviations (Stock Synthesis MCMC posterior medians) for the Gould stock, from 2005 to 2023

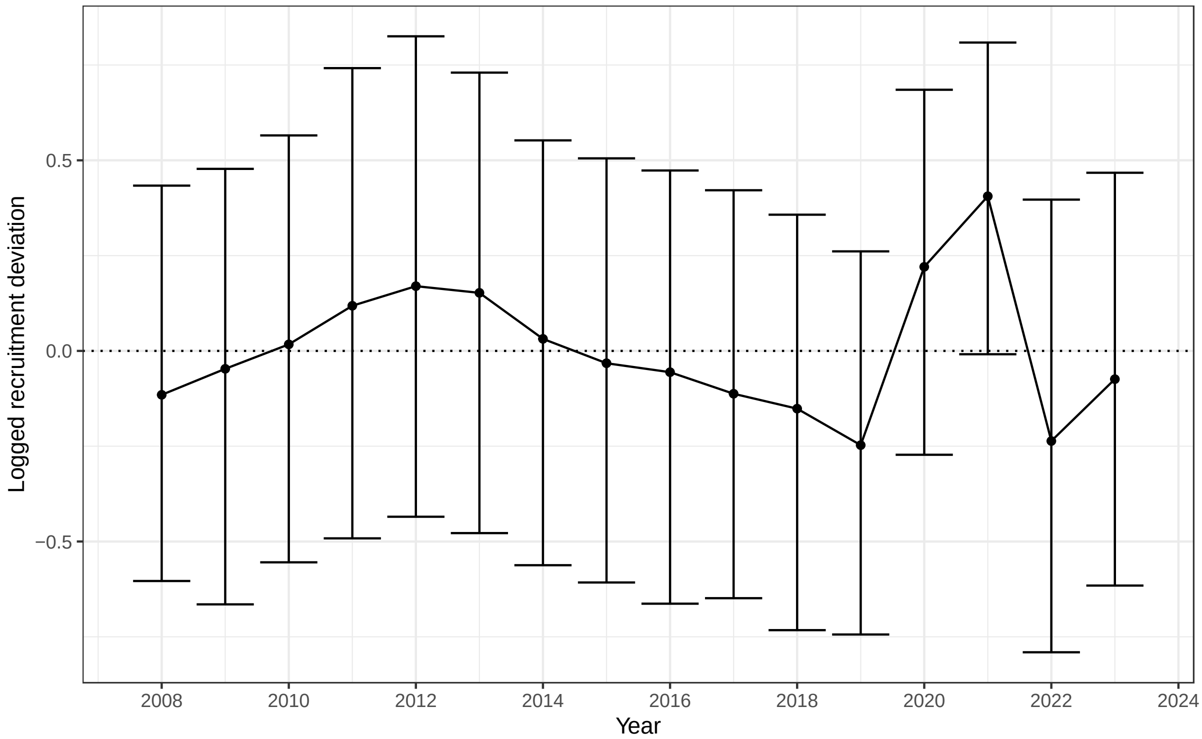


Figure C.10: Recruitment deviations (Stock Synthesis MCMC posterior medians) for the Bunker stock, from 2008 to 2023

C.5 Fishing mortality

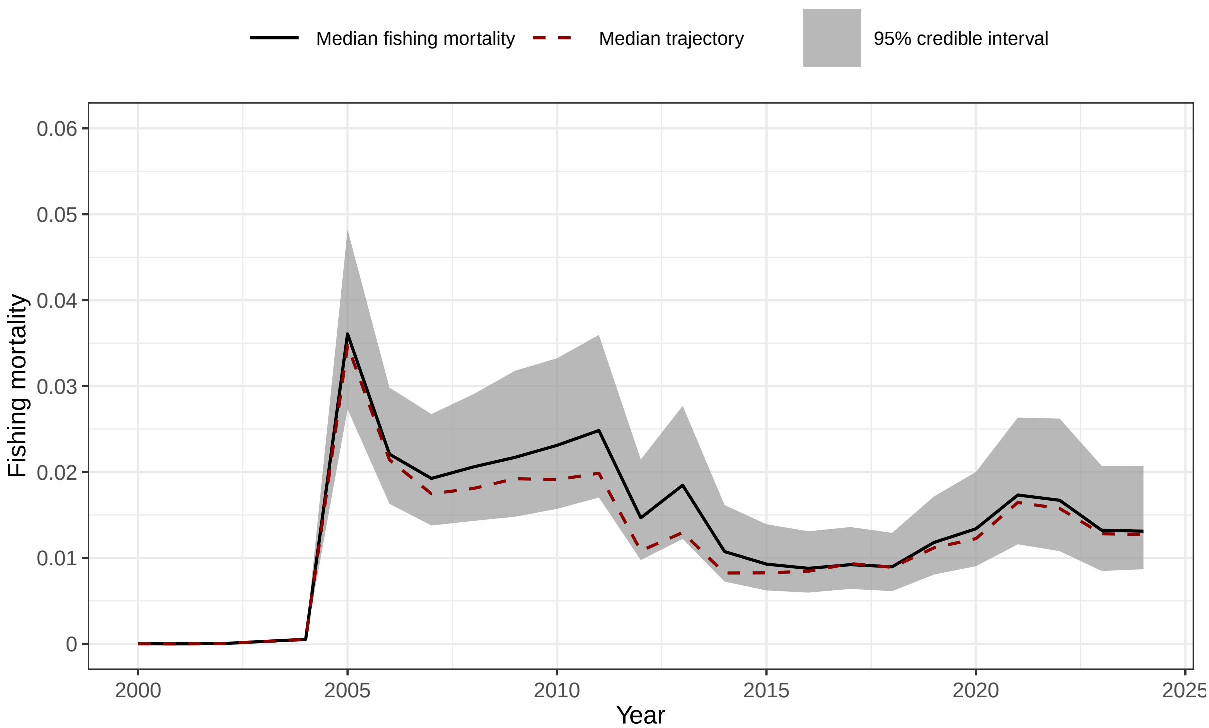


Figure C.11: Predicted legal-sized F from Stock Synthesis MCMC and MLE for the Gould stock, from 2000 to 2023

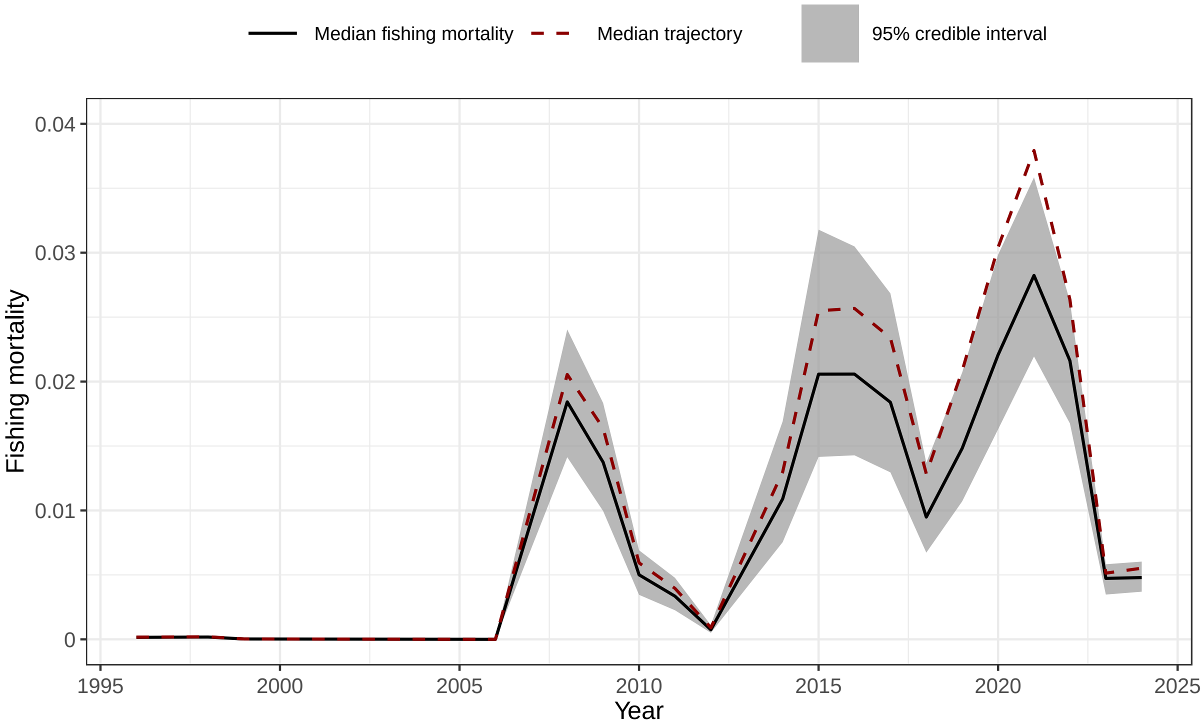


Figure C.12: Predicted legal-sized F from Stock Synthesis MCMC and MLE for the Bunker stock, from 1996 to 2023

Appendix D DDUST base case outputs

D.1 Biomass

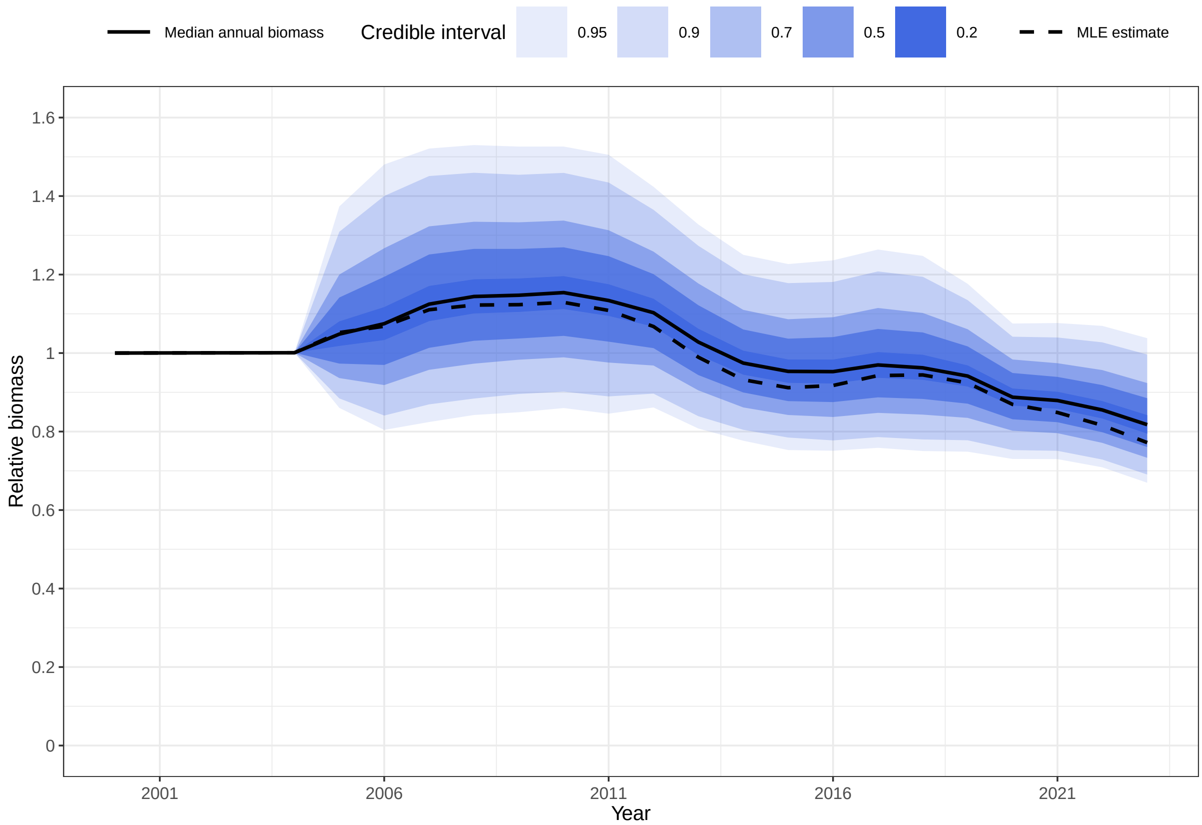


Figure D.1: MCMC predicted biomass trajectory relative to unfished from the DDUST model for the Gould stock, from 2000 to 2023. Blue shading indicates the biomass Bayesian credibility interval.

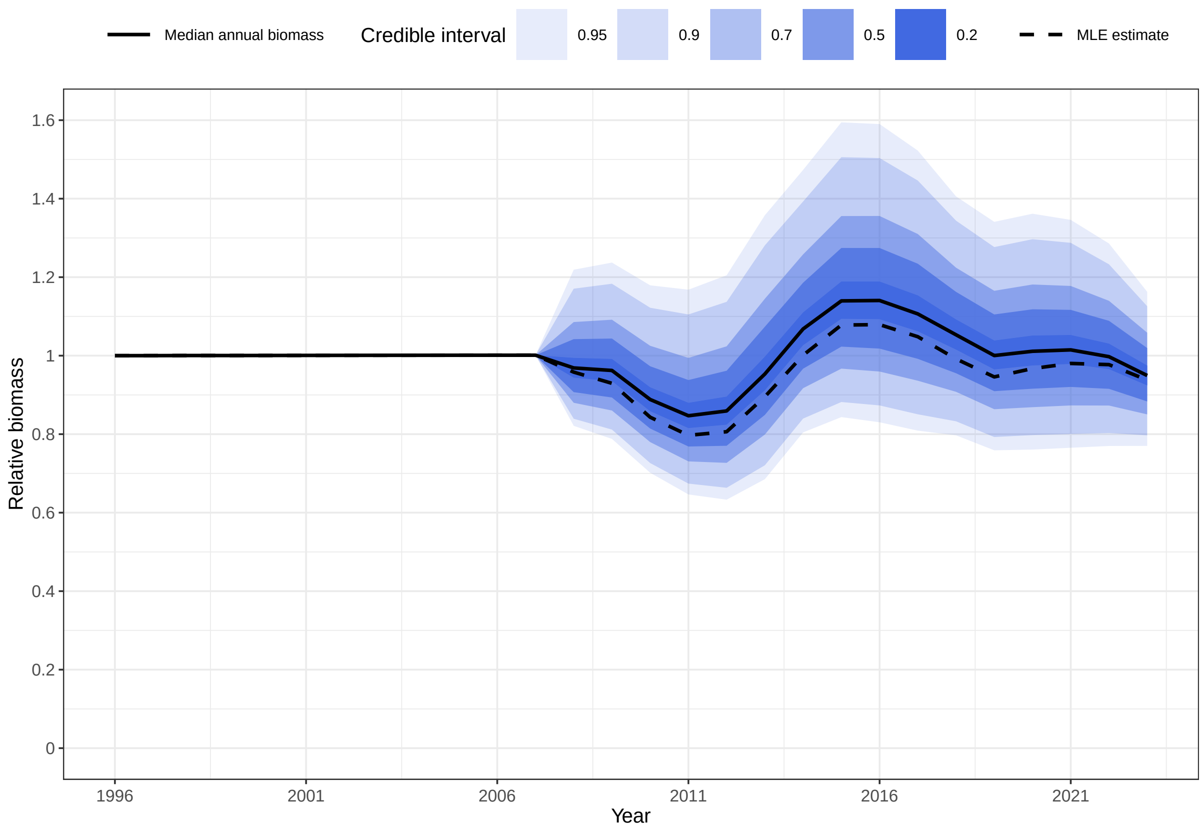


Figure D.2: MCMC predicted biomass trajectory relative to unfished from the DDUST model for the Bunker stock, from 1996 to 2023. Blue shading indicates the biomass Bayesian credibility interval.

D.2 Abundance indices

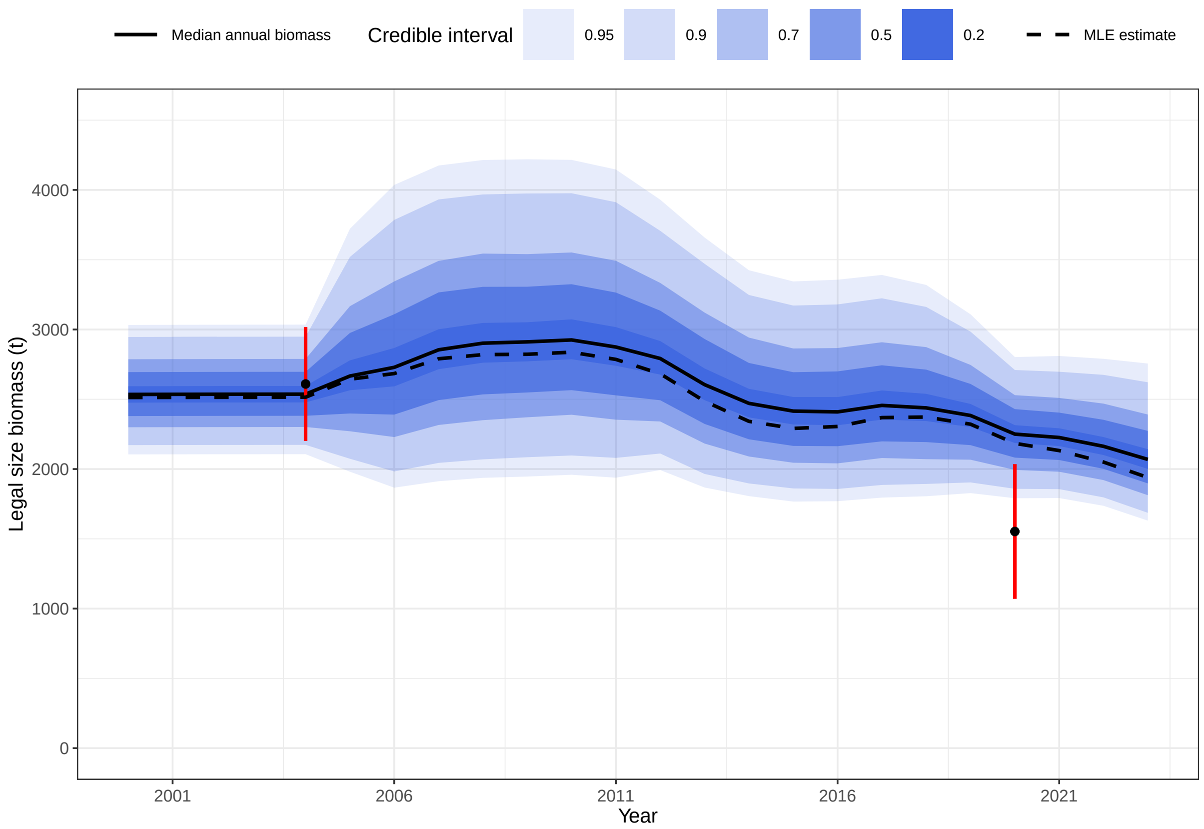


Figure D.3: DDUST model fits to legal-sized biomass survey estimate (black point with red error bars indicating the sd of the estimate) for the Gould stock, from 2000 to 2023.

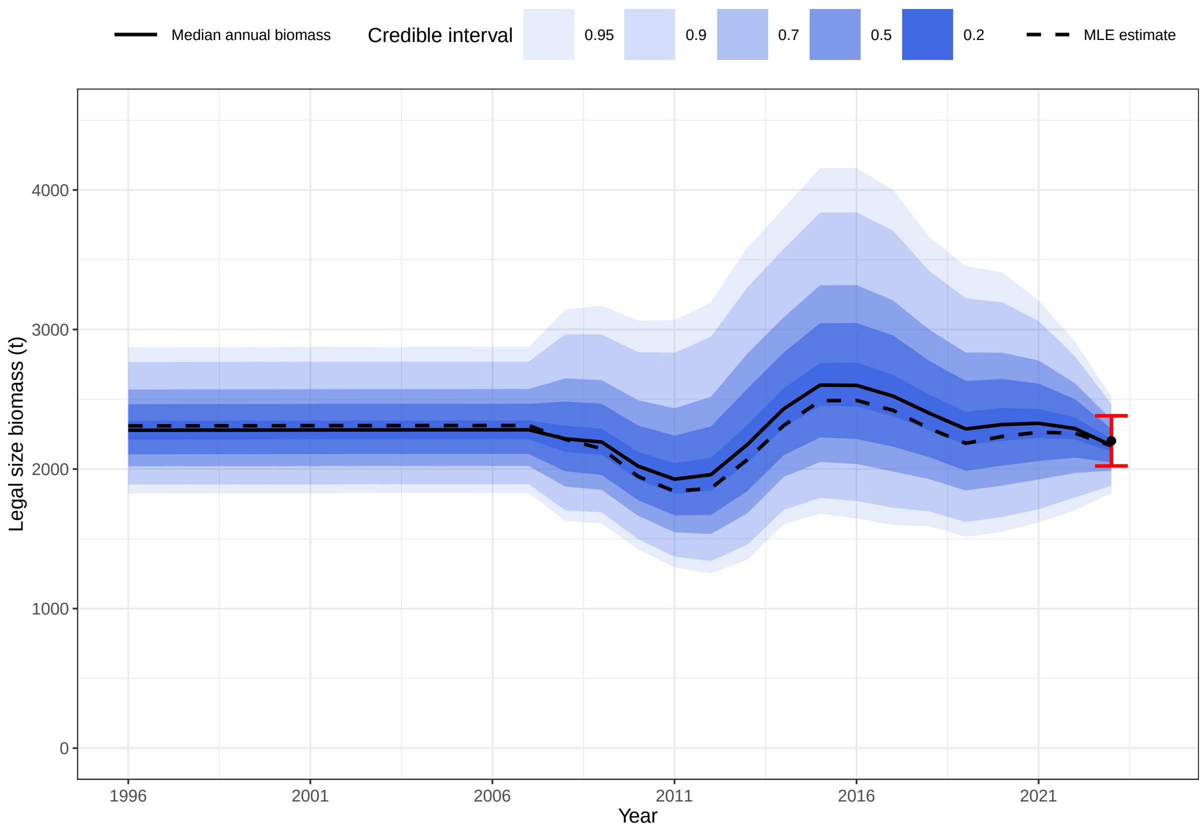


Figure D.4: DDUST model fits to legal-sized biomass survey estimate (black point with red error bars indicating the sd of the estimate) for the Bunker stock, from 1996 to 2023.

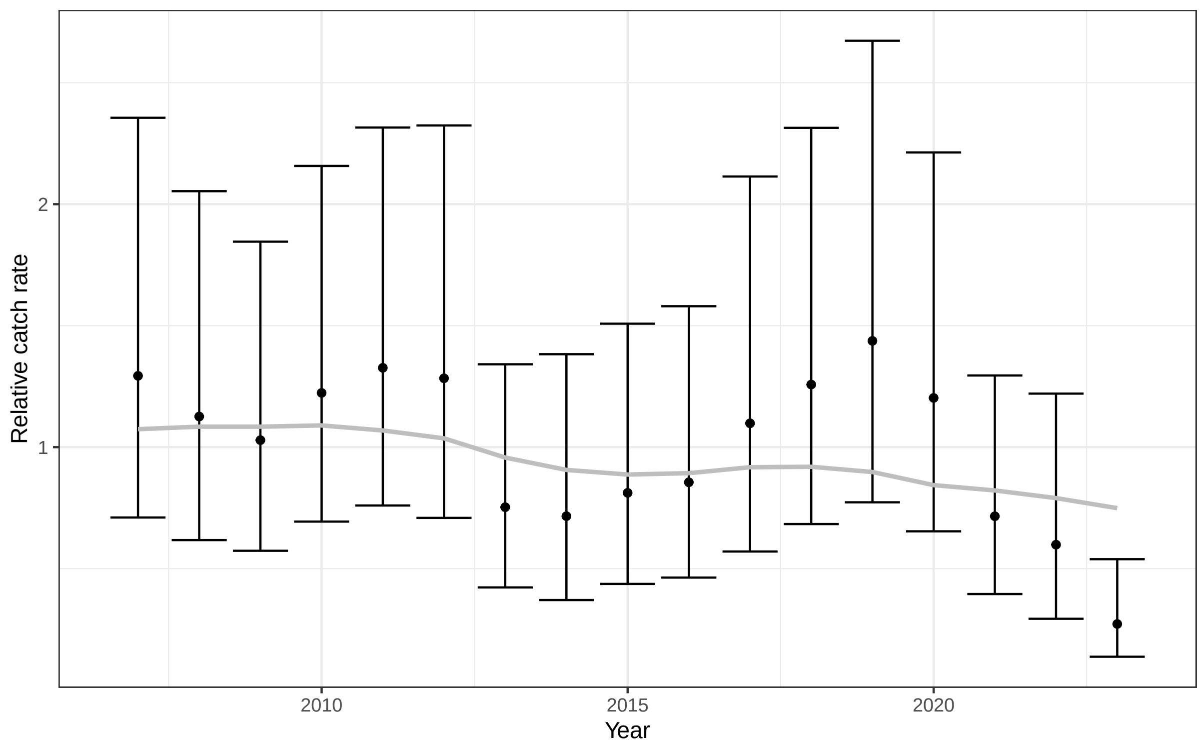


Figure D.5: DDUST model MLE estimates of commercial catch rates for the Gould stock, from 2007 to 2023.

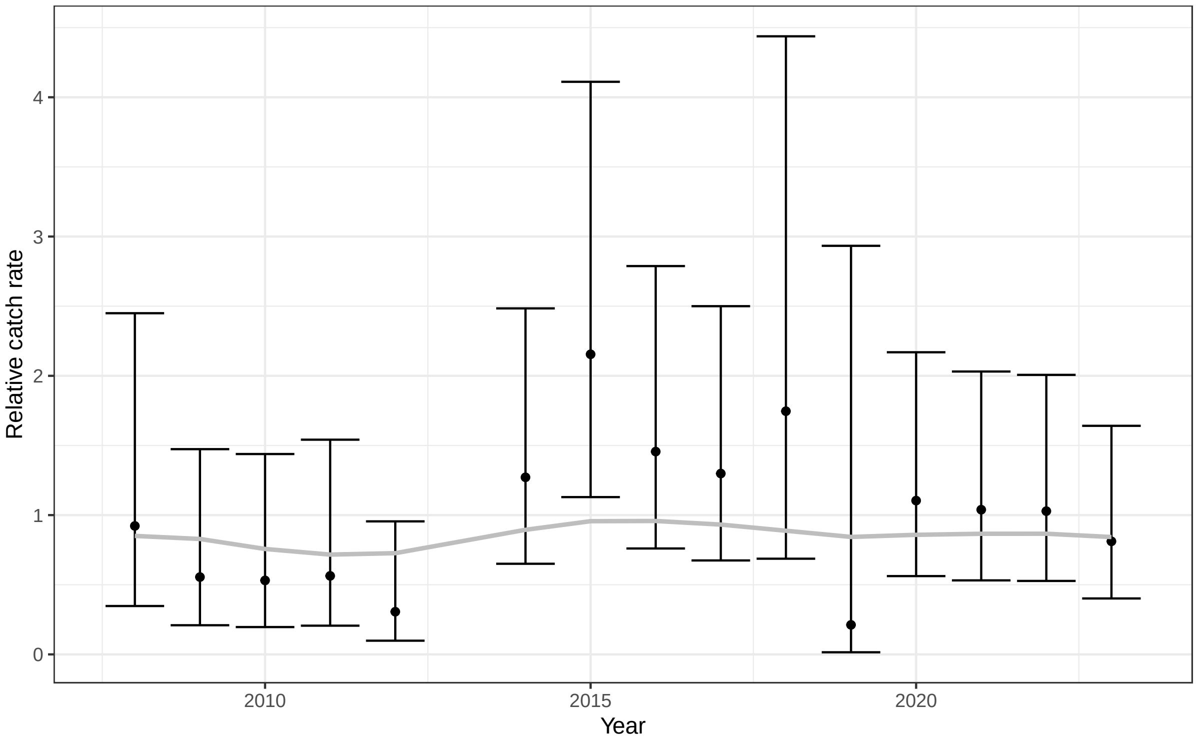


Figure D.6: DDUST model MLE estimates of commercial catch rates for the Bunker stock, from 2008 to 2023.

D.3 Stock-recruitment curve

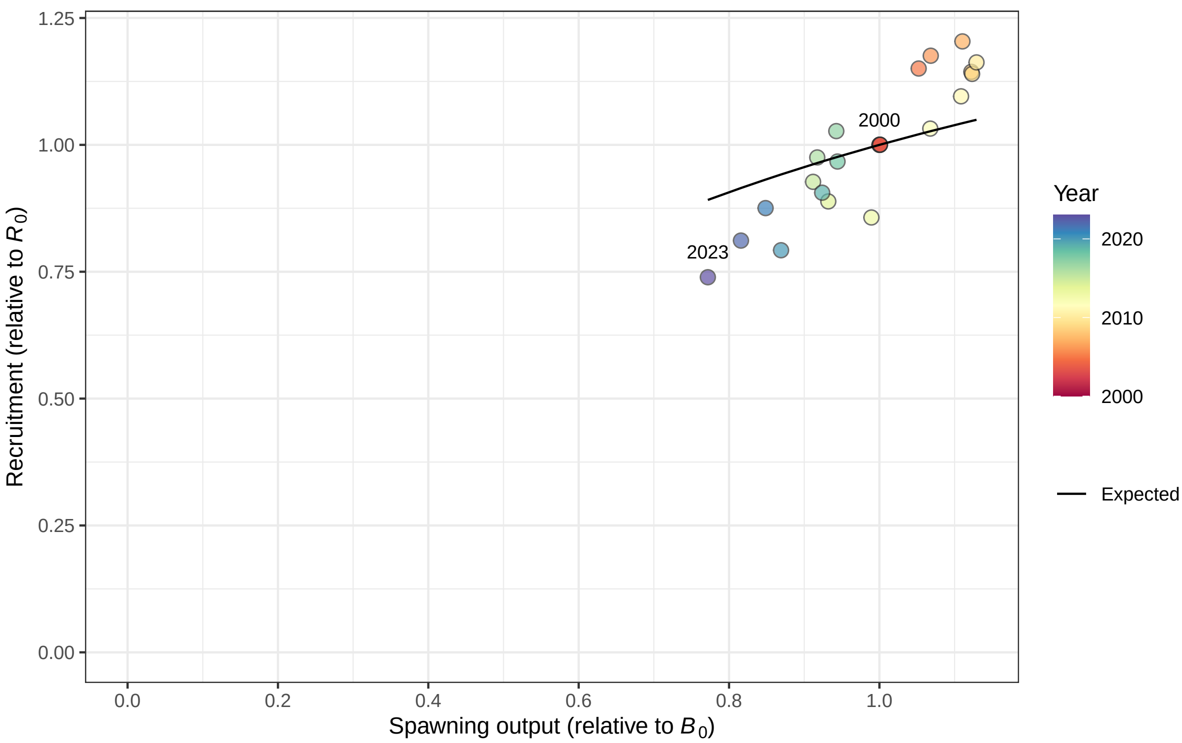


Figure D.7: Stock-recruitment curve estimated via MLE for the Gould stock. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

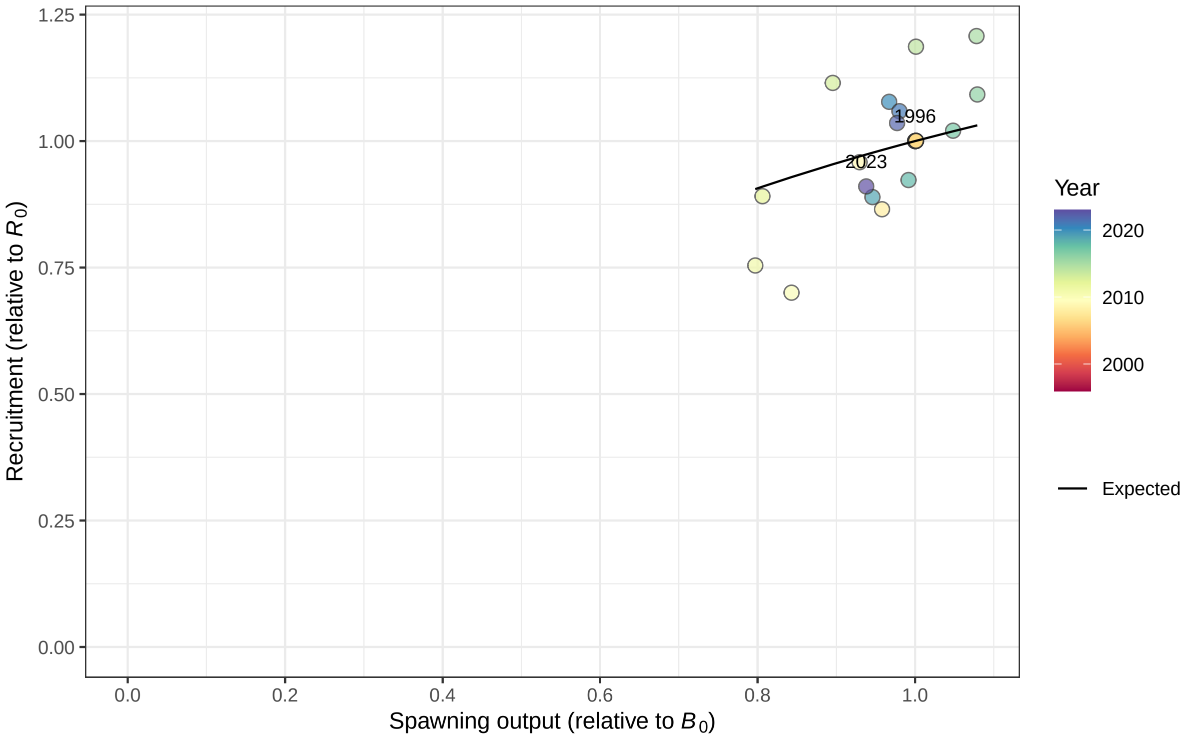


Figure D.8: Stock-recruitment curve estimated via MLE for the Bunker stock. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

D.4 Recruitment deviations

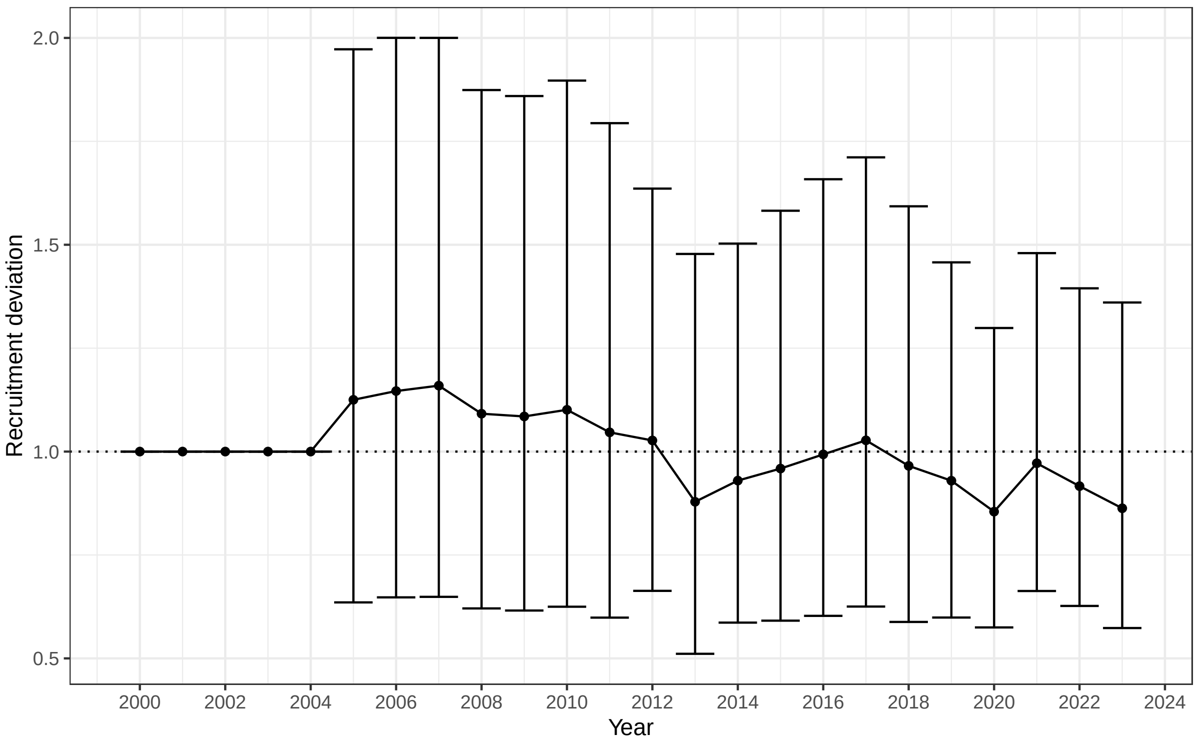


Figure D.9: Recruitment deviations (MCMC posterior medians) for the Gould stock, from 2000 to 2023.

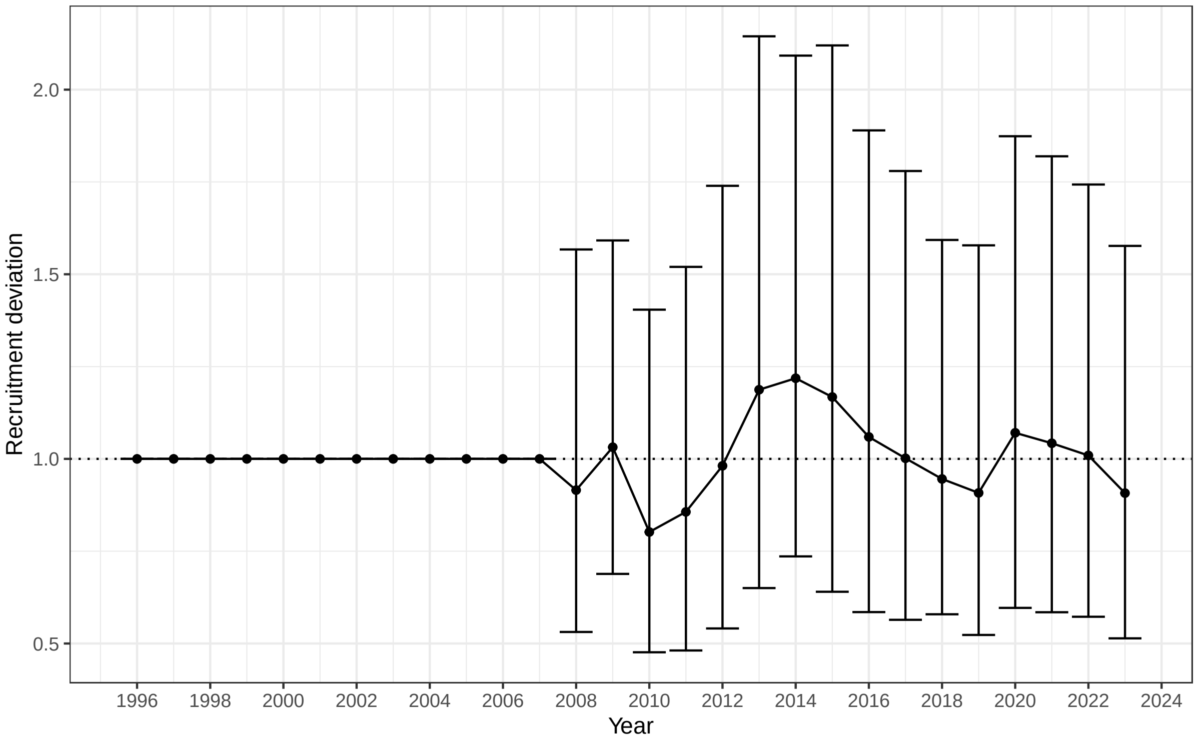


Figure D.10: Recruitment deviations (MCMC posterior medians) for the Bunker stock, from 1996 to 2023.

D.5 Fishing mortality

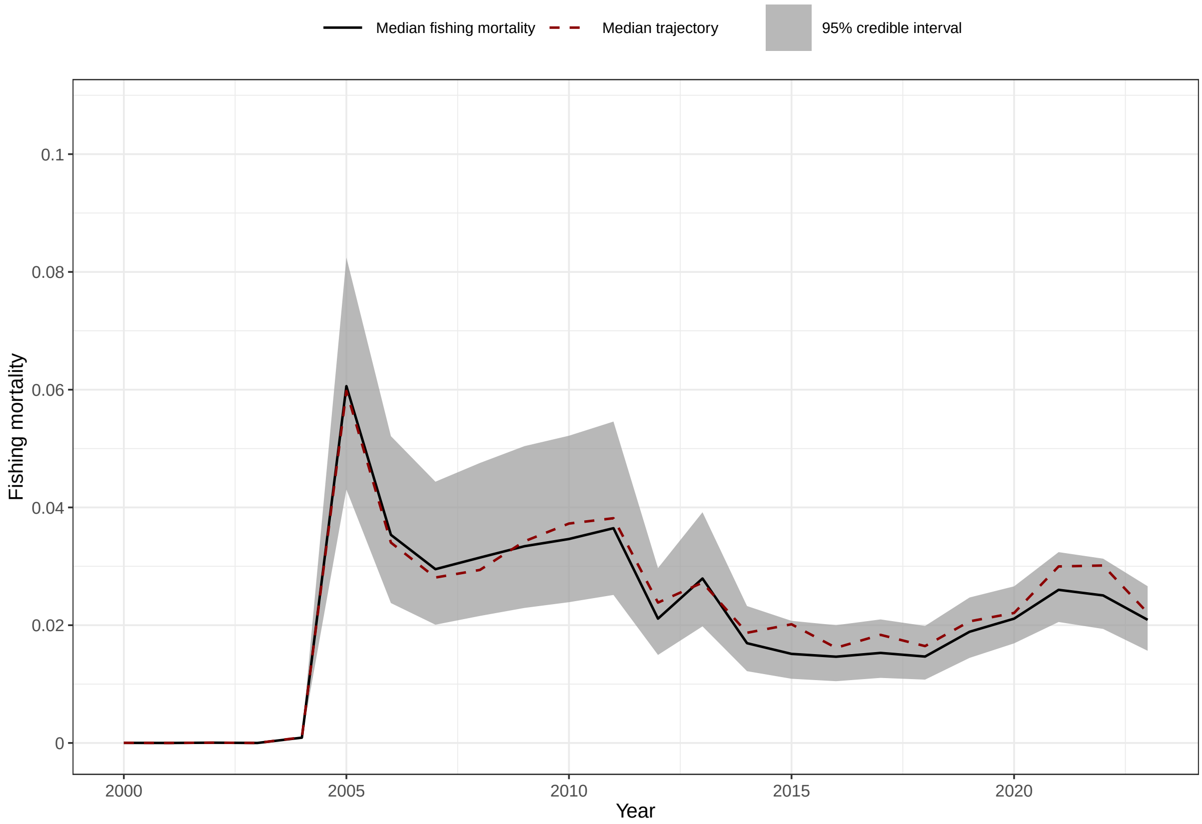


Figure D.11: Predicted legal-sized F from DDUST MCMC and MLE for the Gould stock, from 2000 to 2023

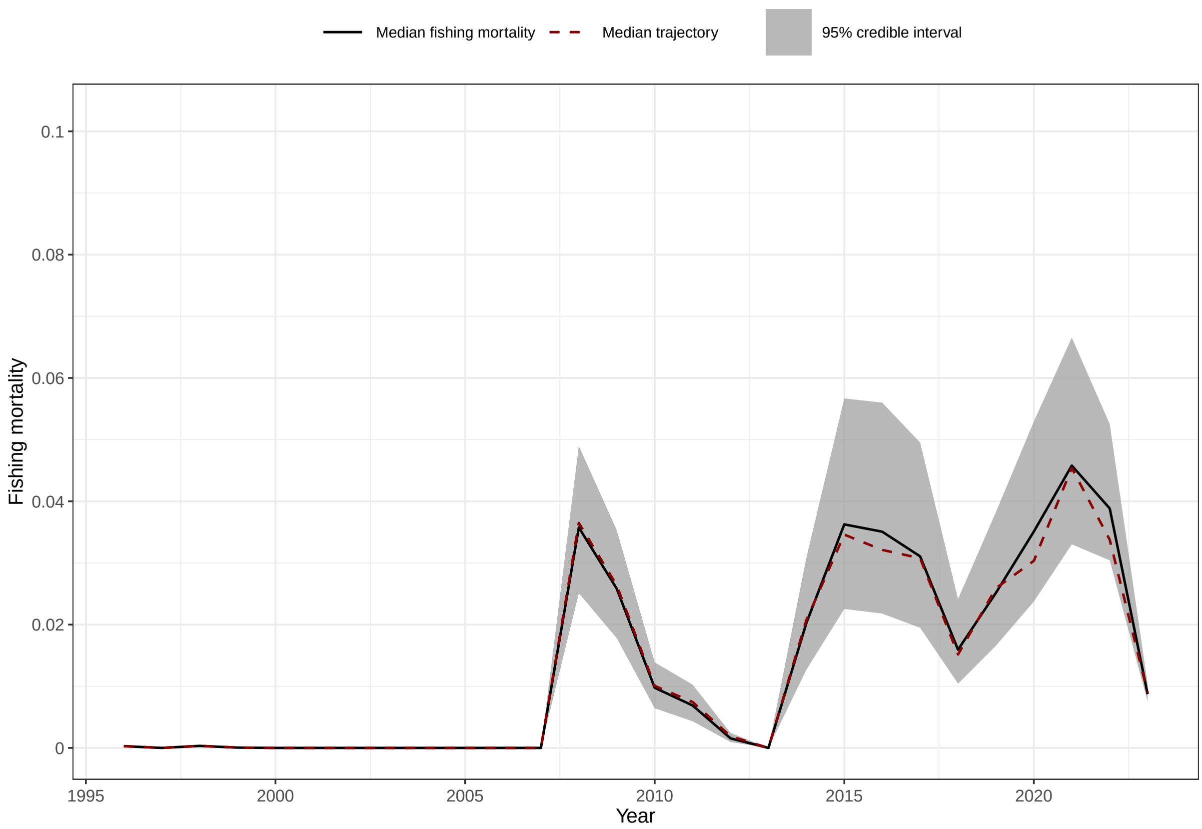


Figure D.12: Predicted legal-sized F from DDUST MCMC and MLE for the Bunker stock, from 1996 to 2023

Appendix E Stock Synthesis MCMC diagnostics

E.1 Potential scale reduction factor

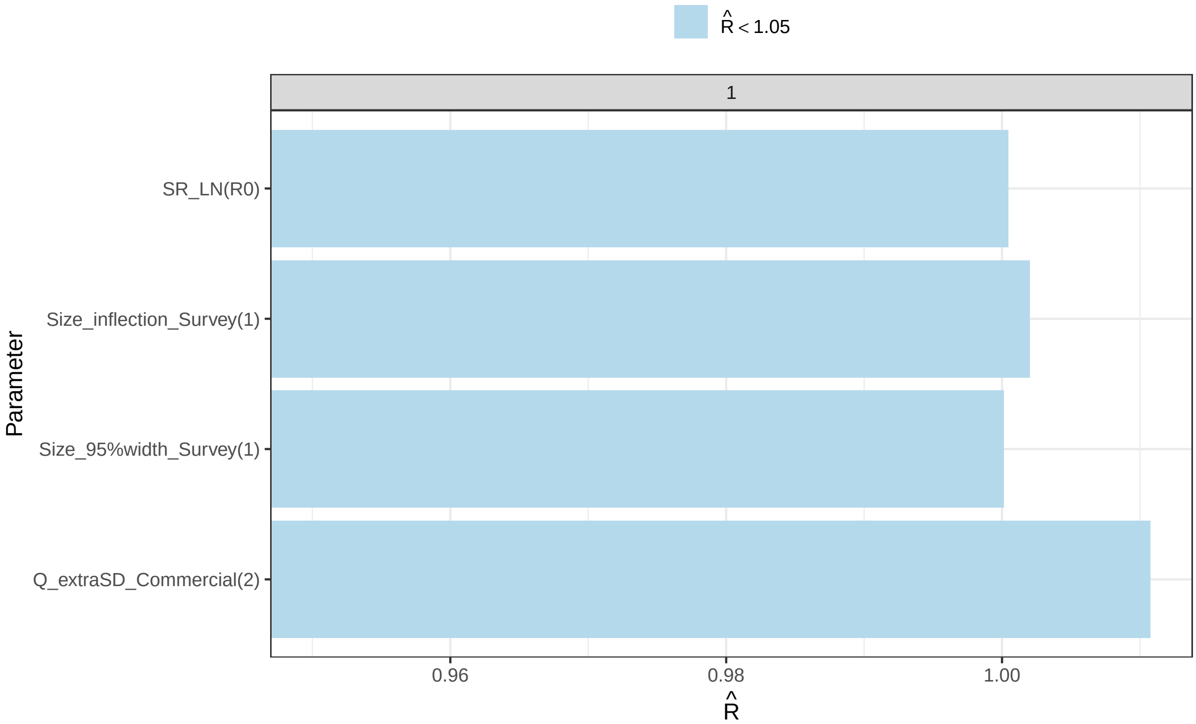


Figure E.1: Potential scale reduction factor plots for the Gould stock base case scenario.

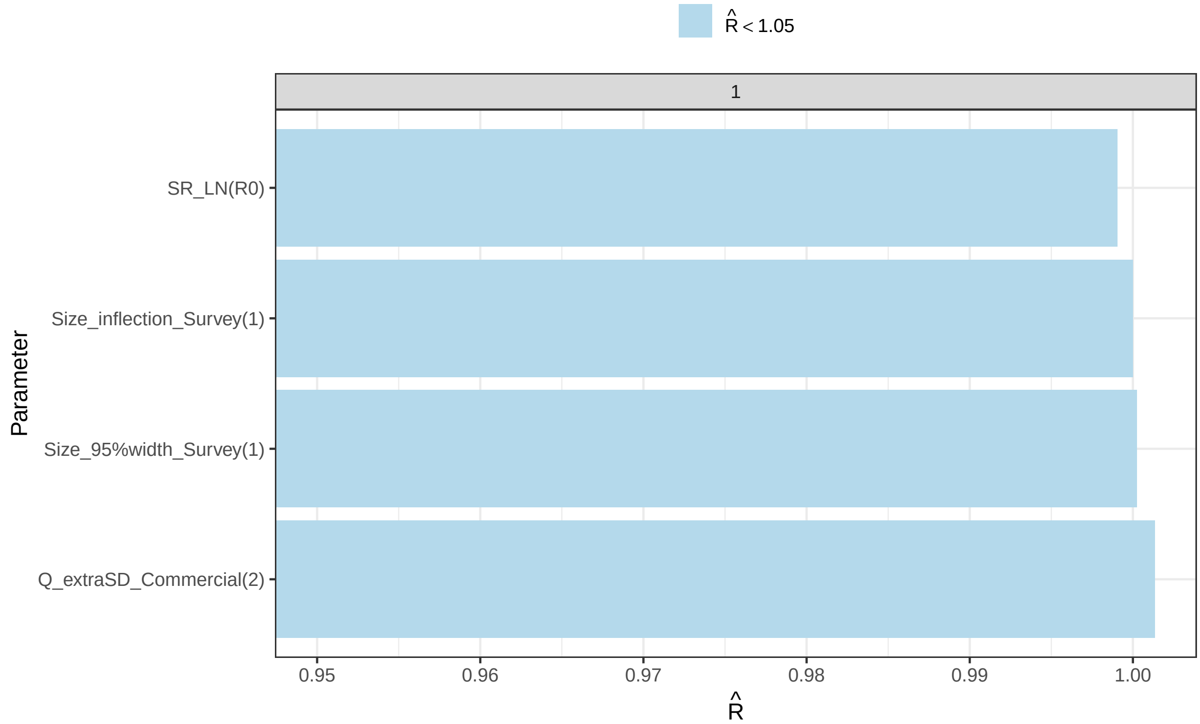


Figure E.2: Potential scale reduction factor plots for the Bunker stock base case scenario.

E.2 Posterior density plots

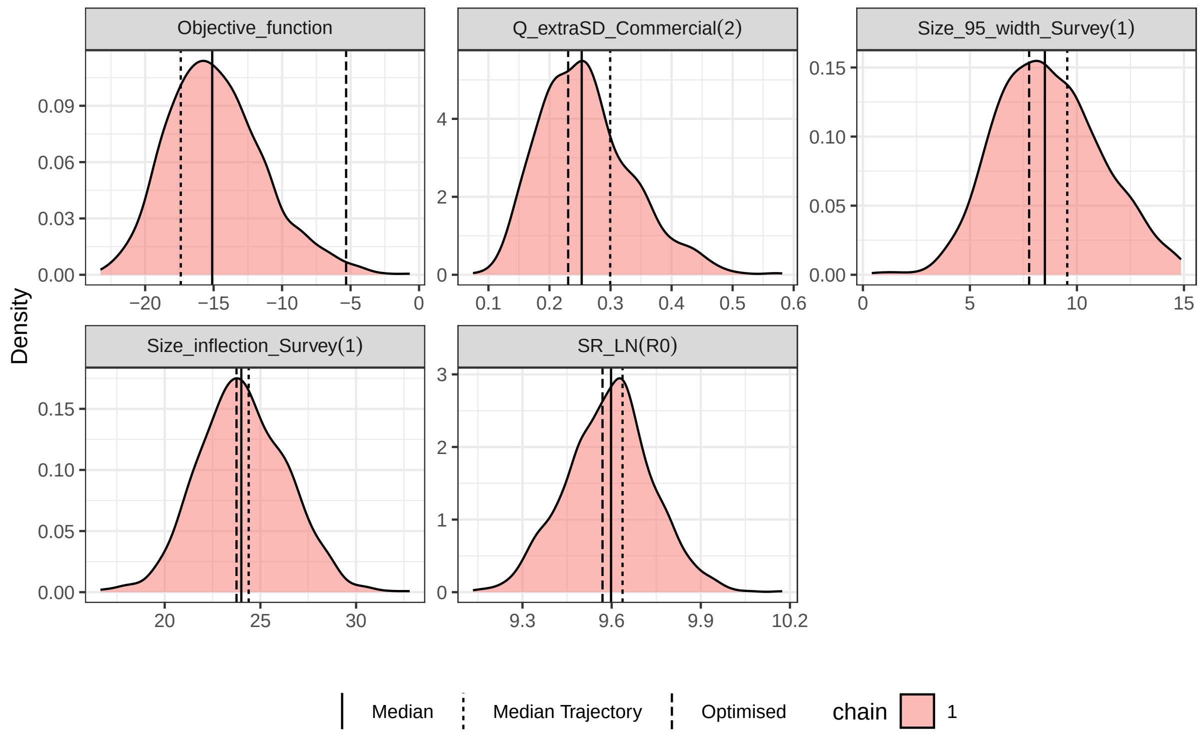


Figure E.3: Posterior density plots for the Gould stock base case Stock Synthesis model.

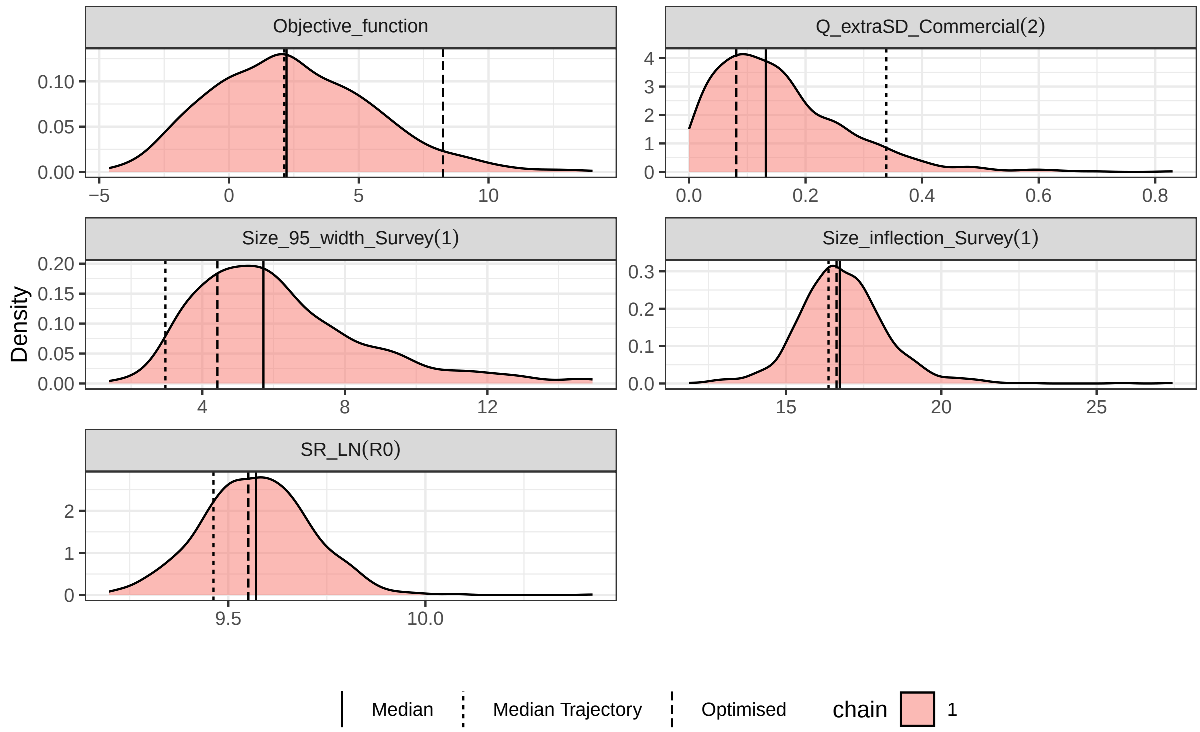


Figure E.4: Posterior density plots for the Bunker stock base case Stock Synthesis model.

E.3 Trace plots

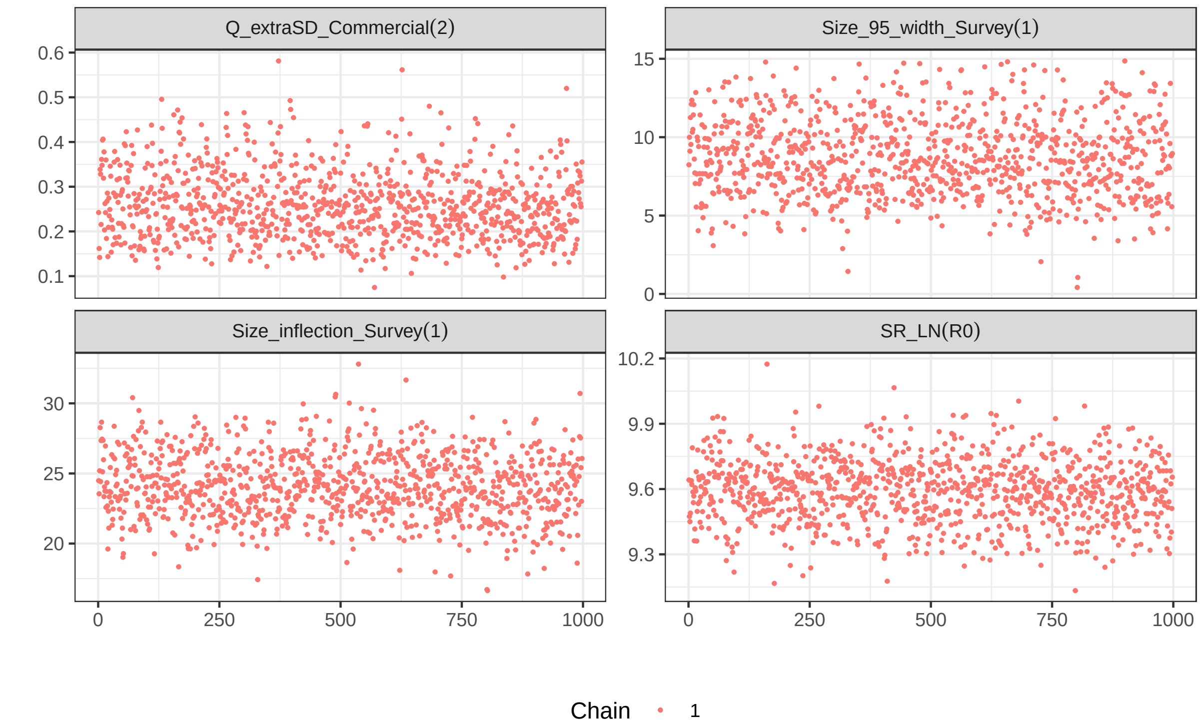


Figure E.5: Trace plots for the Gould stock base case Stock Synthesis model.

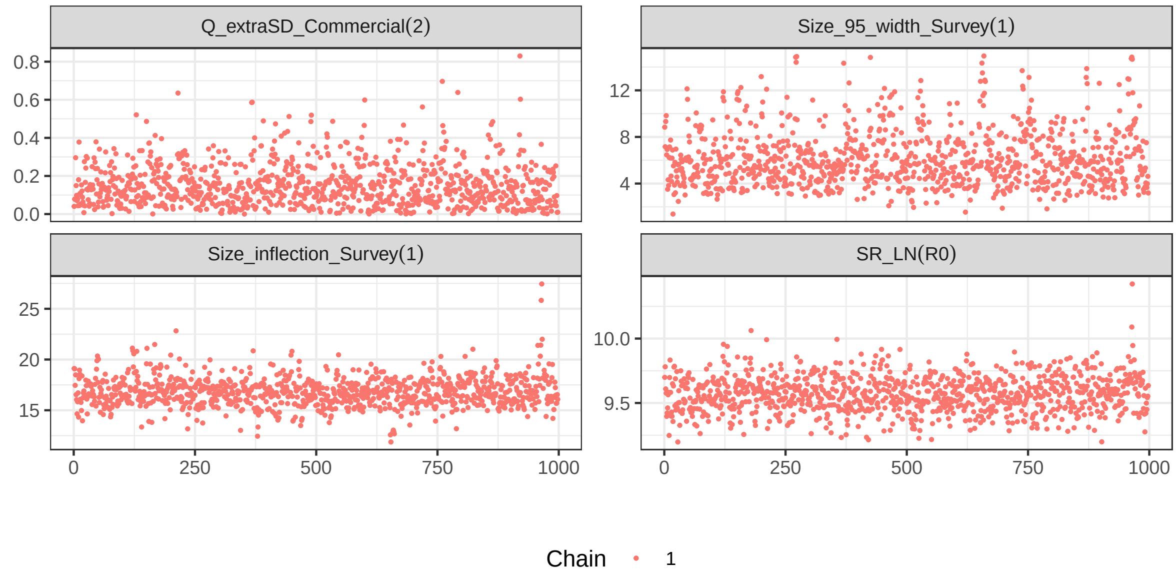


Figure E.6: Trace plots for the Bunker stock base case Stock Synthesis model.

E.4 Correlation plots

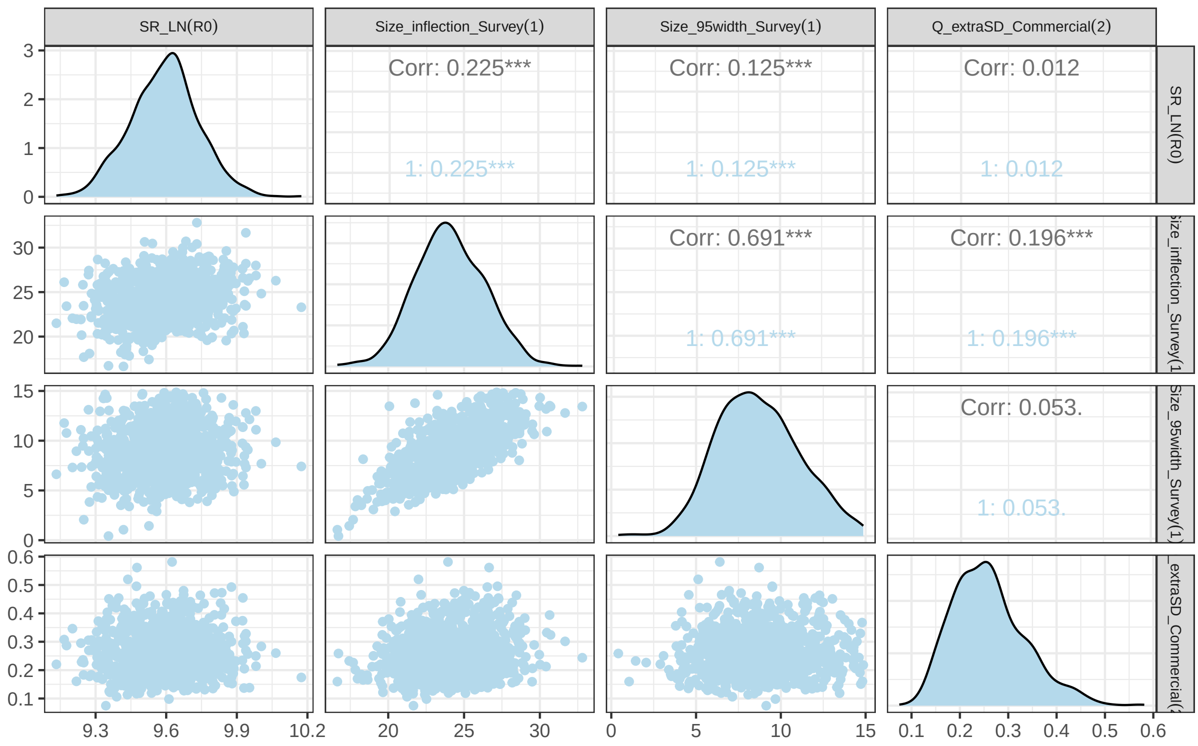


Figure E.7: Parameter correlation plots for the Gould stock base case Stock Synthesis model.

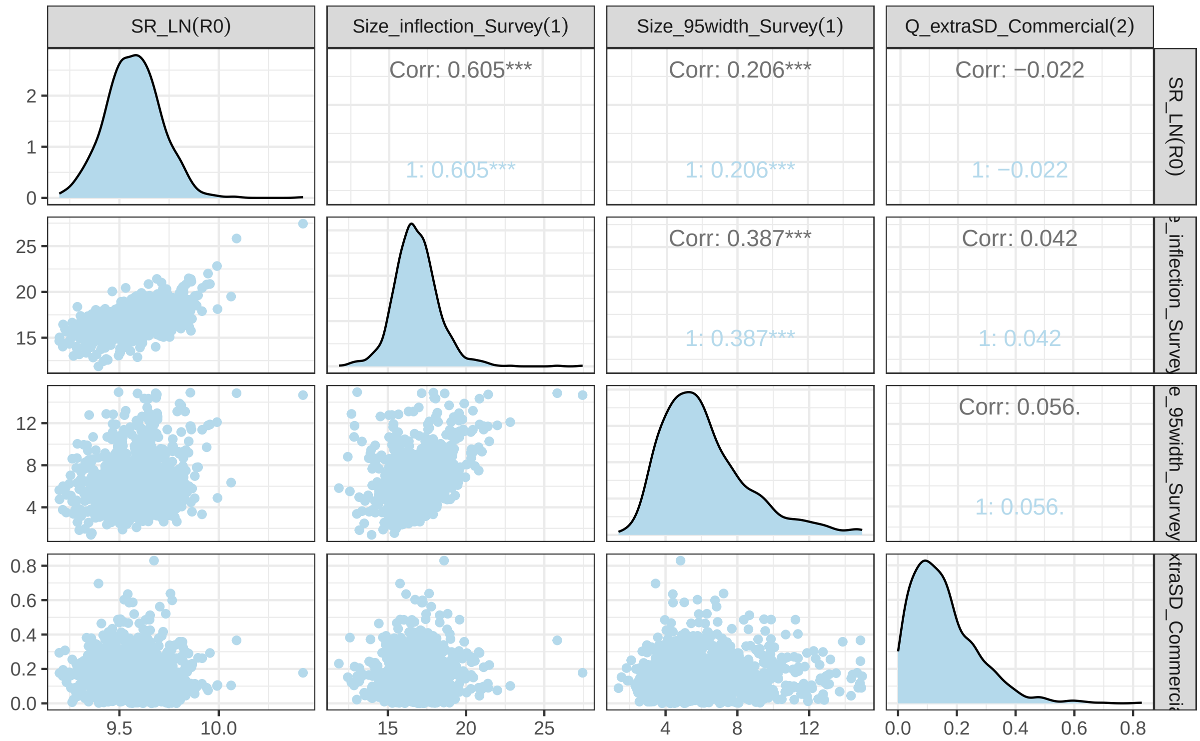


Figure E.8: Parameter correlation plots for the Bunker stock base case Stock Synthesis model.

E.5 Natural mortality likelihood profile plots

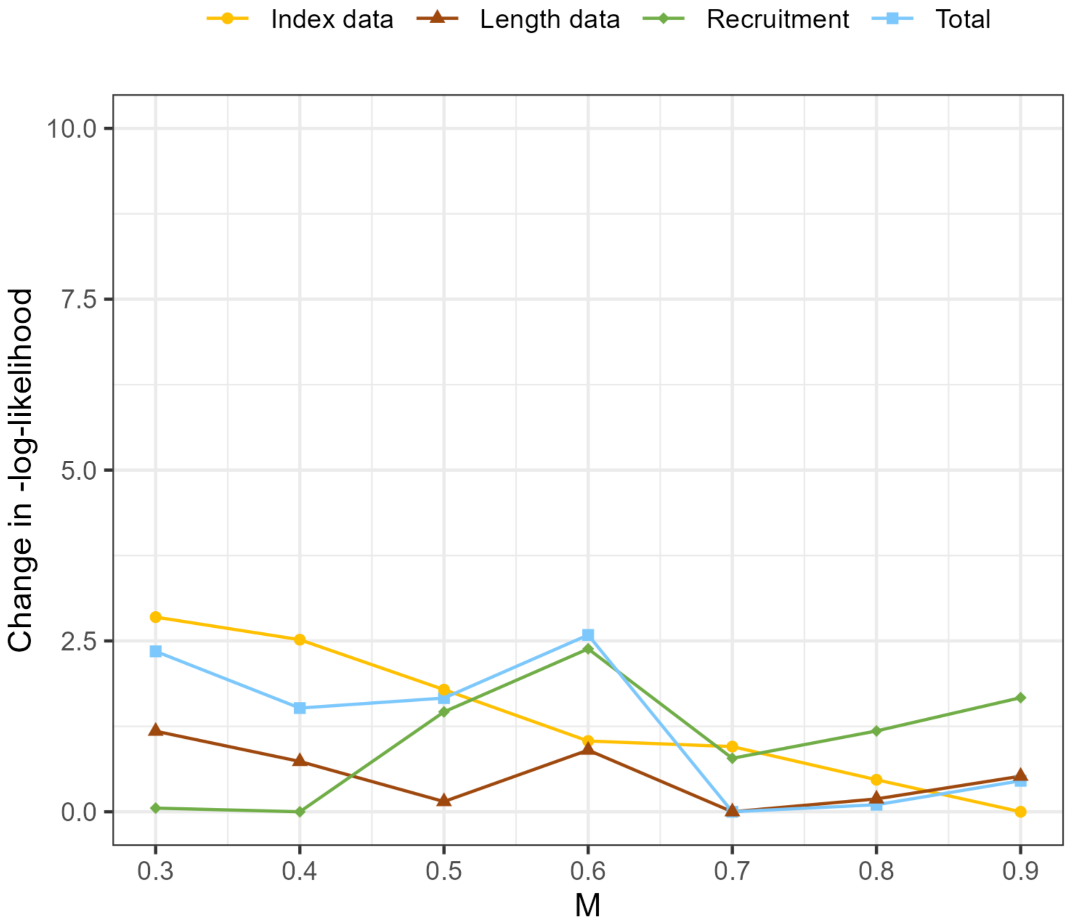


Figure E.9: Natural mortality (M) likelihood profile for the Gould stock base case Stock Synthesis model.

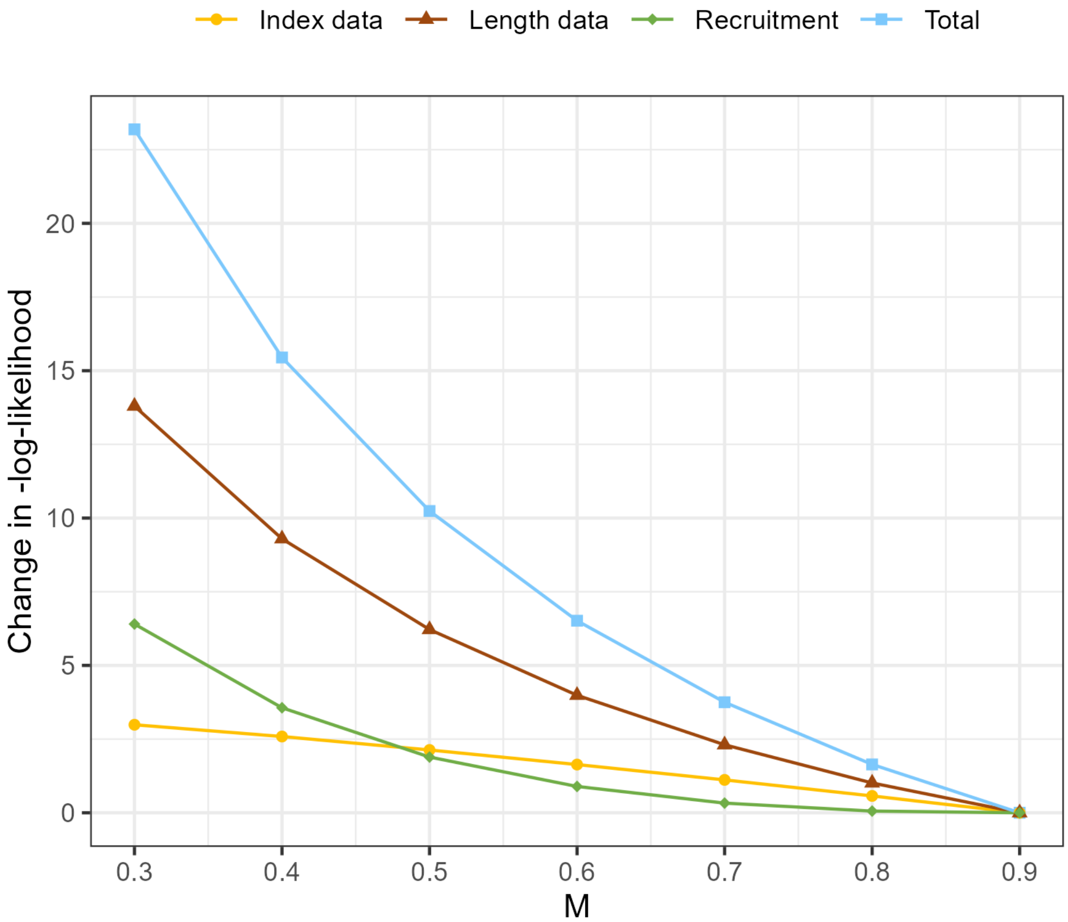


Figure E.10: Natural mortality (M) likelihood profile for the Bunker stock base case Stock Synthesis model.

Appendix F DDUST MCMC diagnostics

F.1 Posterior density plots

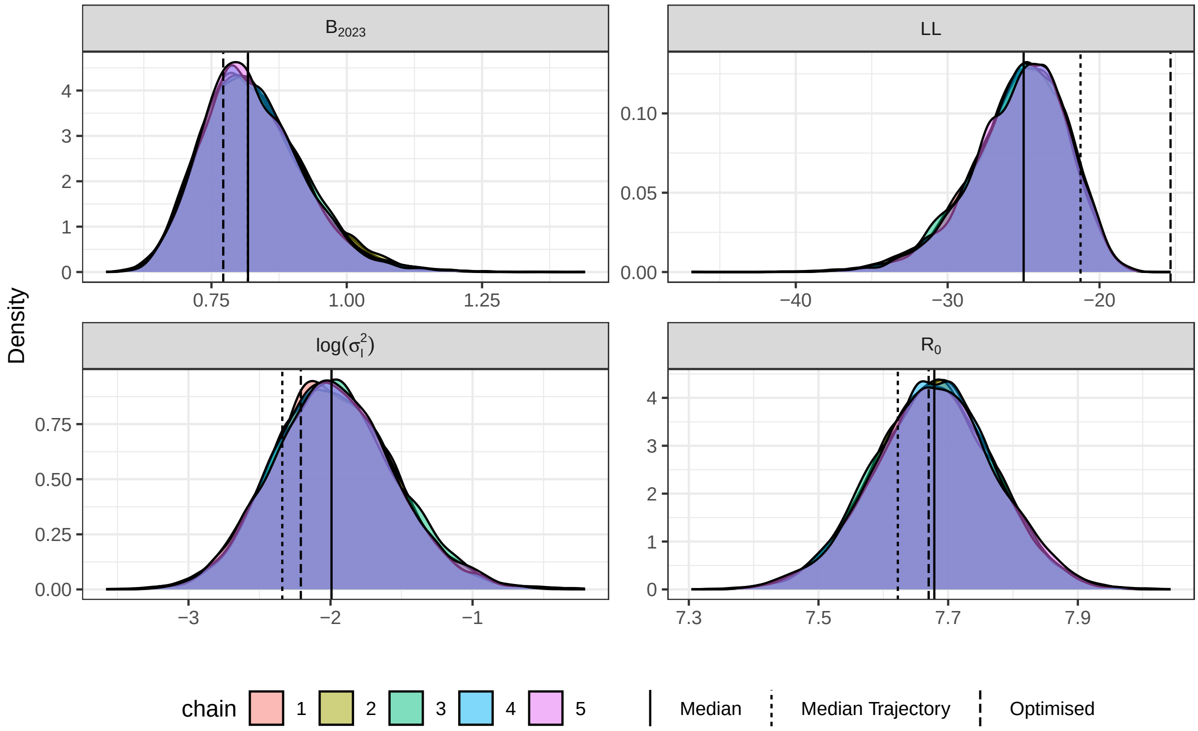


Figure F.1: Posterior density plots for the Gould stock base case DDUST model.

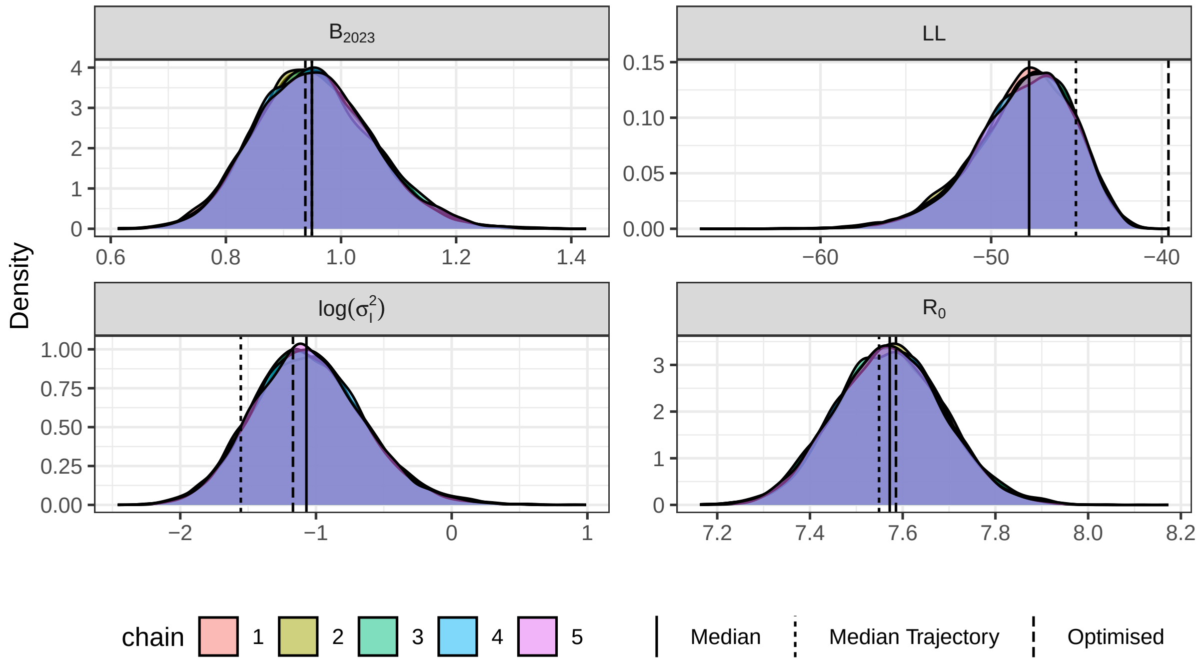


Figure F.2: Posterior density plots for the Bunker stock base case DDUST model.

F.2 Trace plots

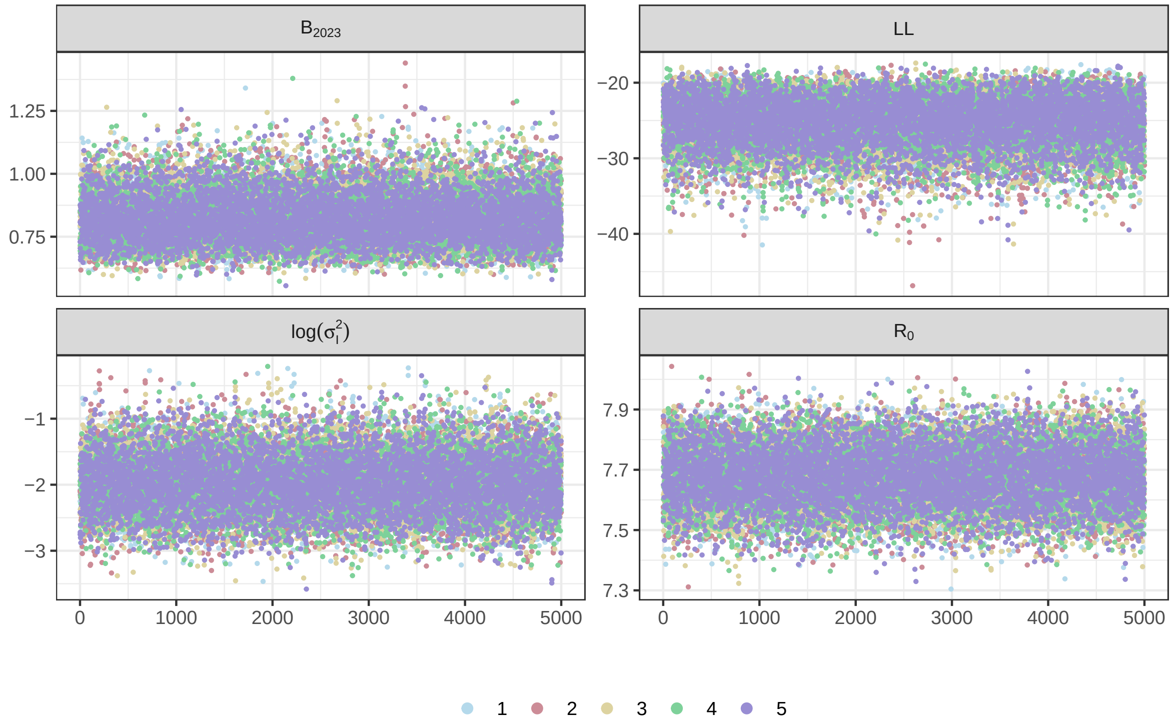


Figure F.3: Trace plots for the Gould stock base case DDUST model.

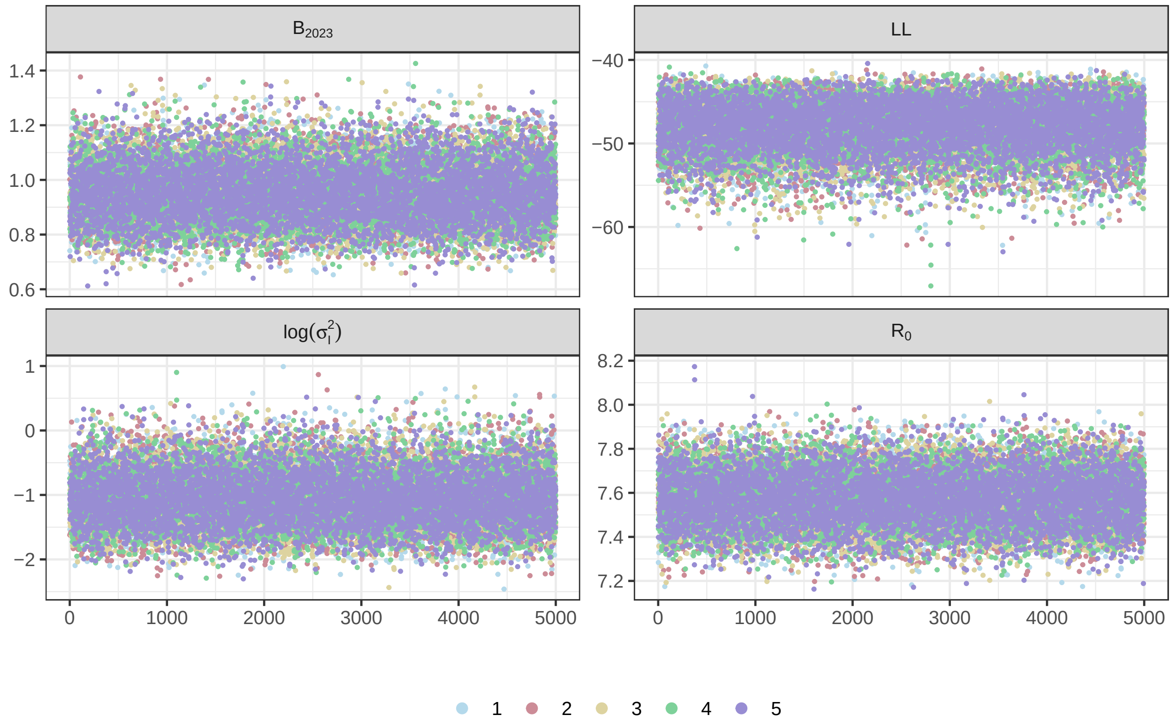


Figure F.4: Trace plots for the Bunker stock base case DDUST model.

F.3 Correlation plots

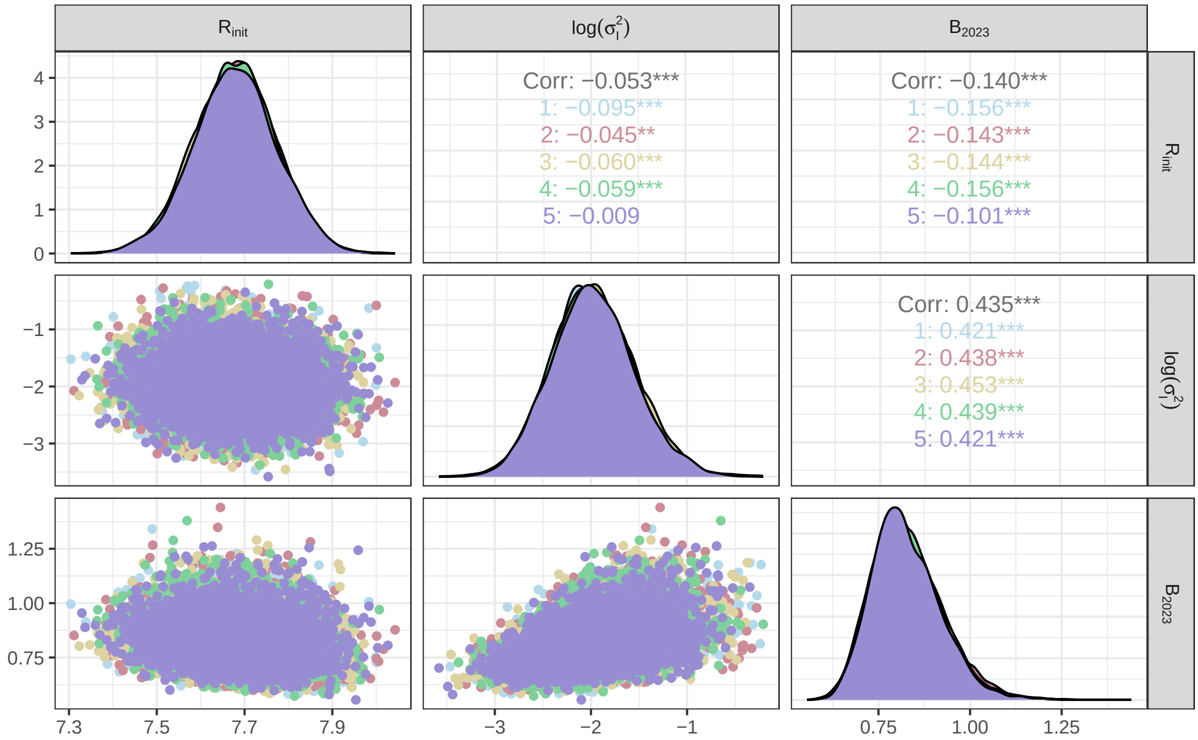


Figure F.5: Parameter correlation plots for the Gould stock base case DDUST model.

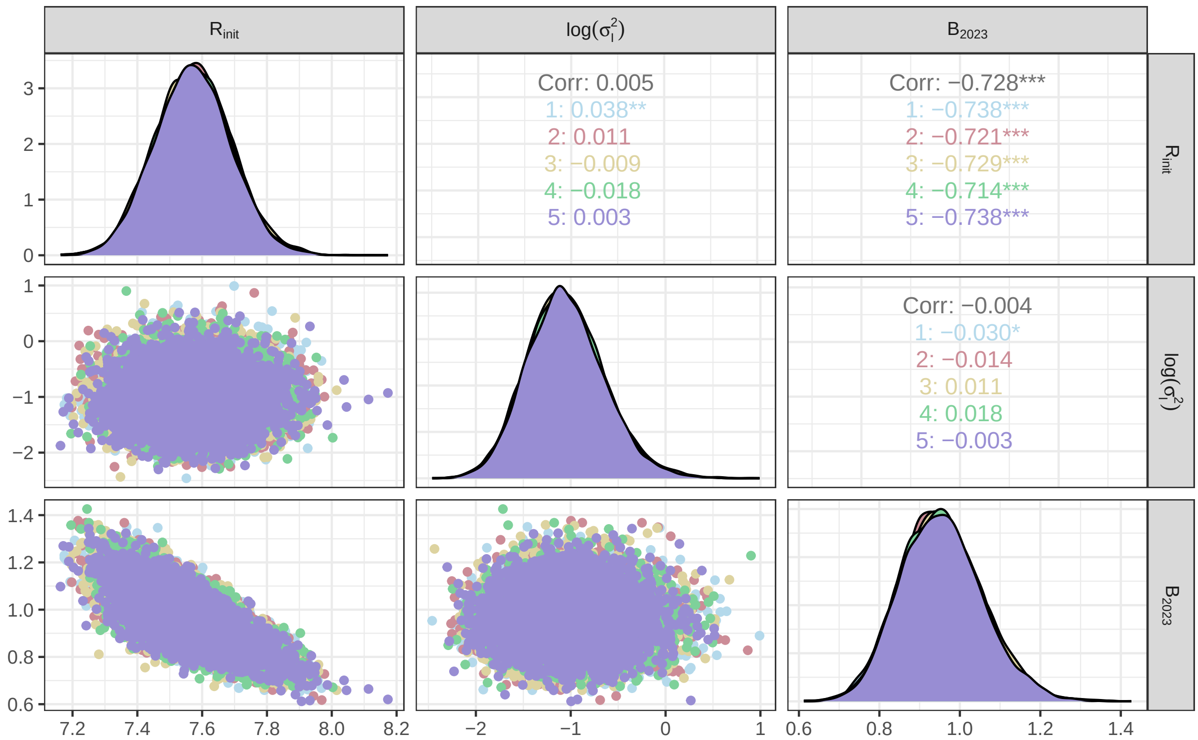


Figure F.6: Parameter correlation plots for the Bunker stock base case DDUST model.

F.4 Natural mortality likelihood profile plots

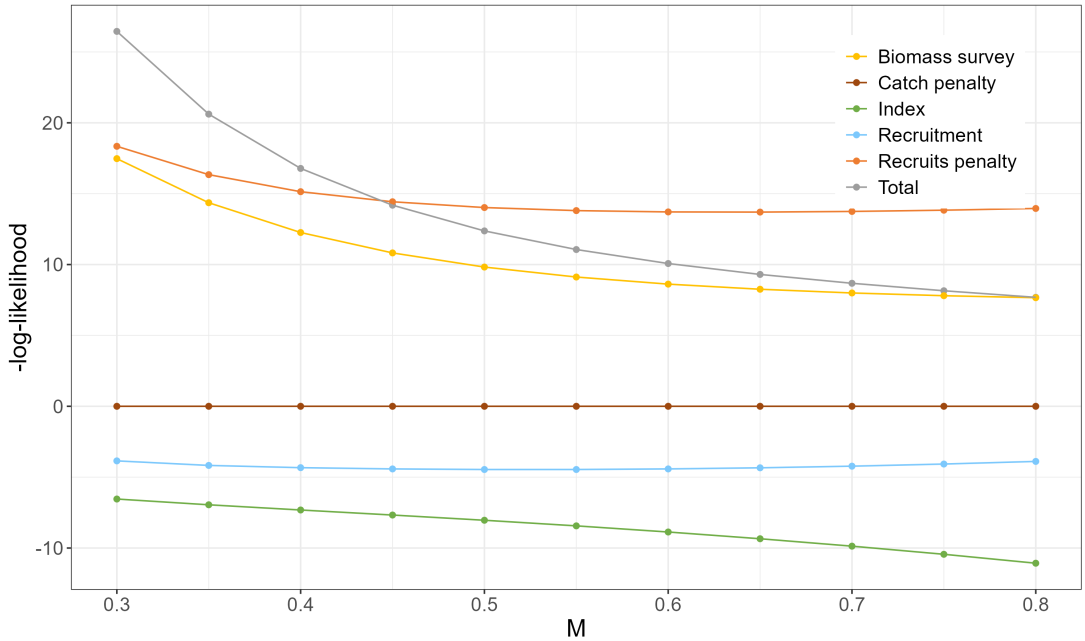


Figure F.7: Natural mortality (M) likelihood profile for the Gould stock base case DDUST model.

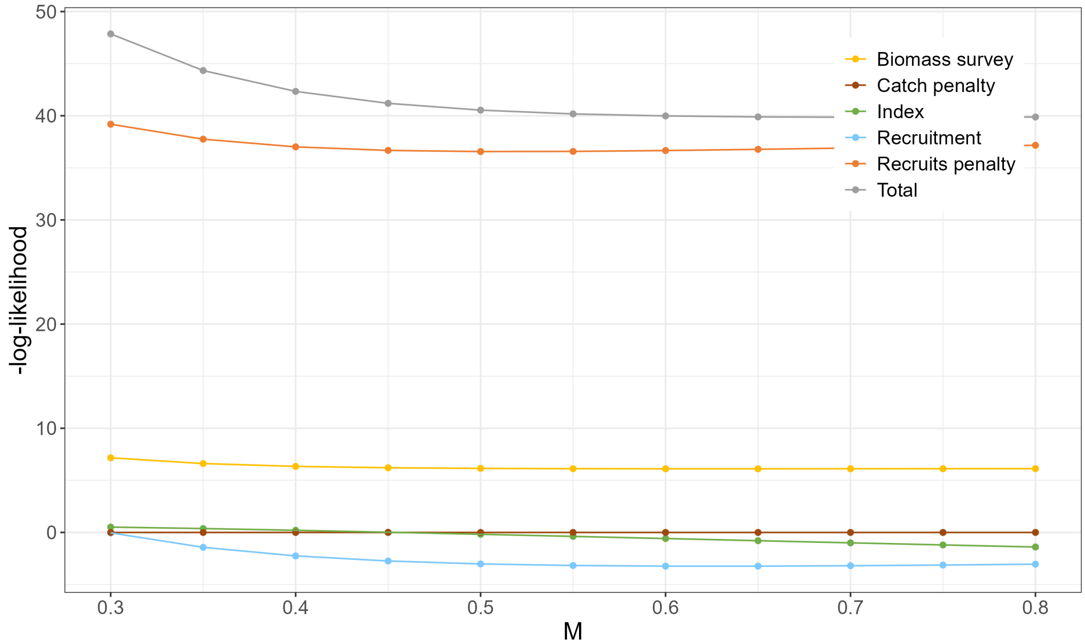


Figure F.8: Natural mortality (M) likelihood profile for the Bunker stock base case DDUST model.

Appendix G Stock Synthesis scenario outputs

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

Scenario	Stocks	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	Slower growth
10	All	Faster growth
11	All	Earlier maturity
12	All	Later maturity
13	All	Older plus group
14	All	Ricker recruitment relationship
15	Bunker	Shrinkage adjustment applied to length composition data

G.1 Sensitivity

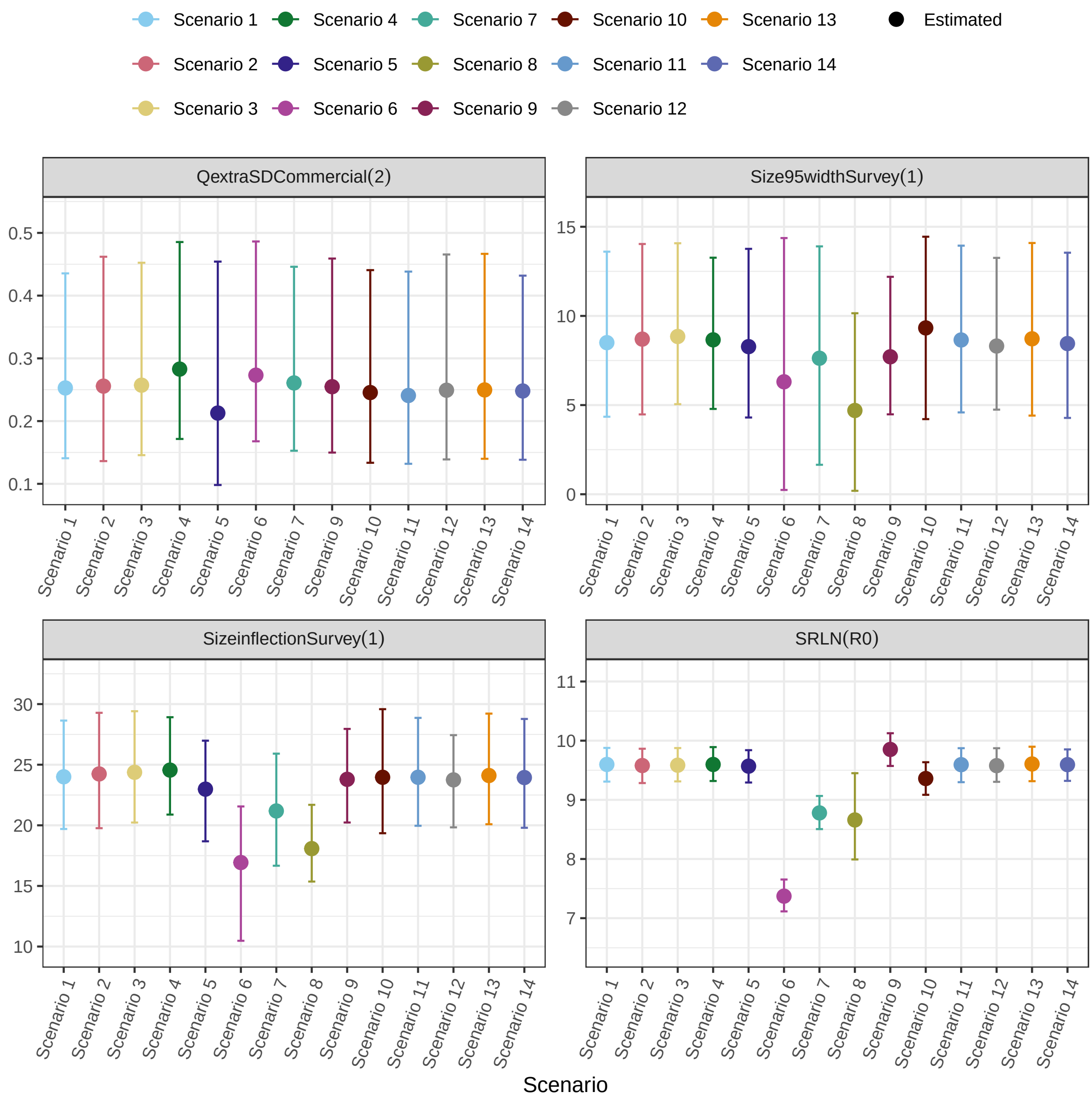


Figure G.1: Stock Synthesis sensitivity plots of estimated parameters for all scenarios for the Gould stock.

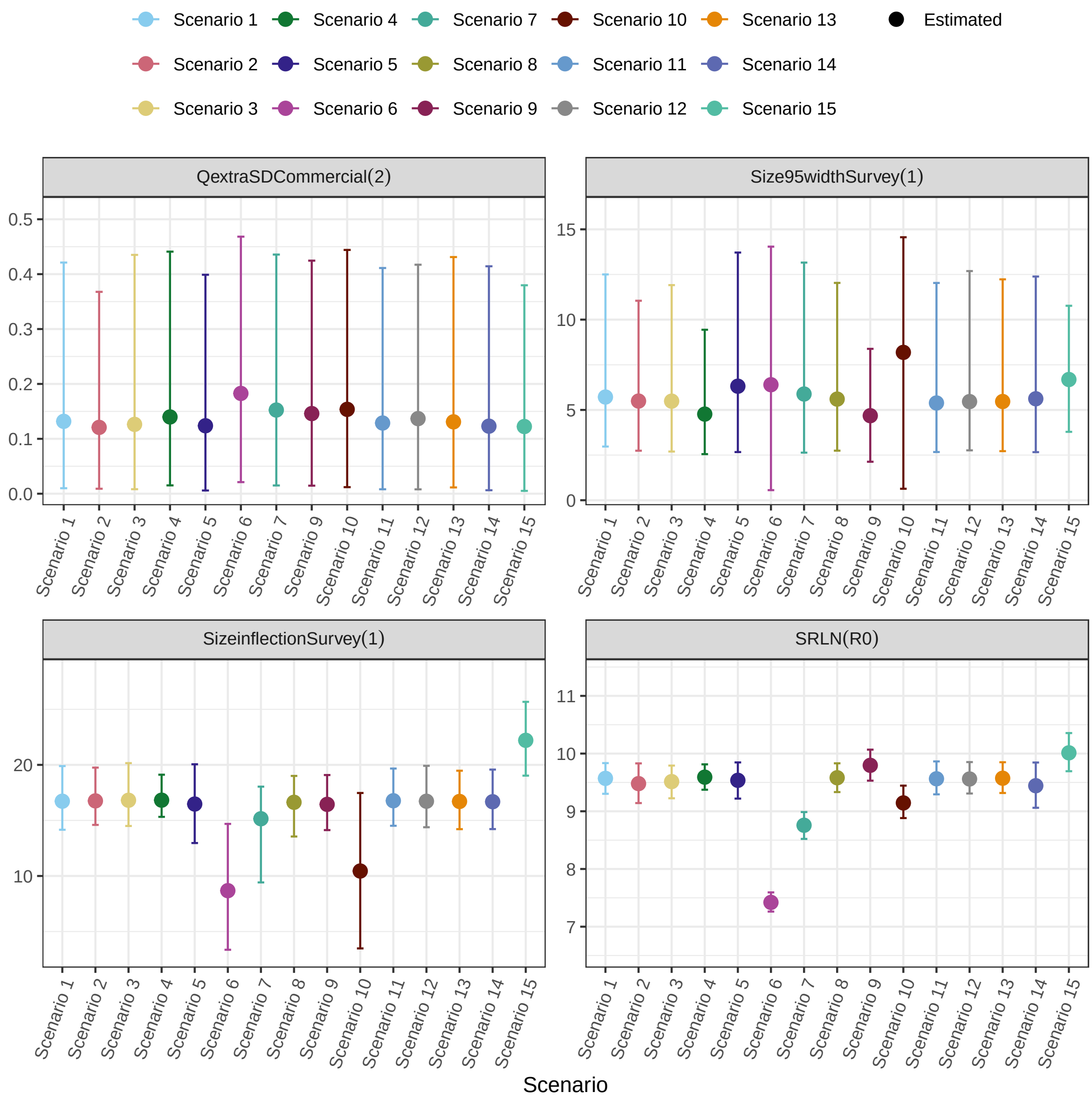


Figure G.2: Stock Synthesis sensitivity plots of estimated parameters for all scenarios for the Bunker stock.

G.2 Biomass

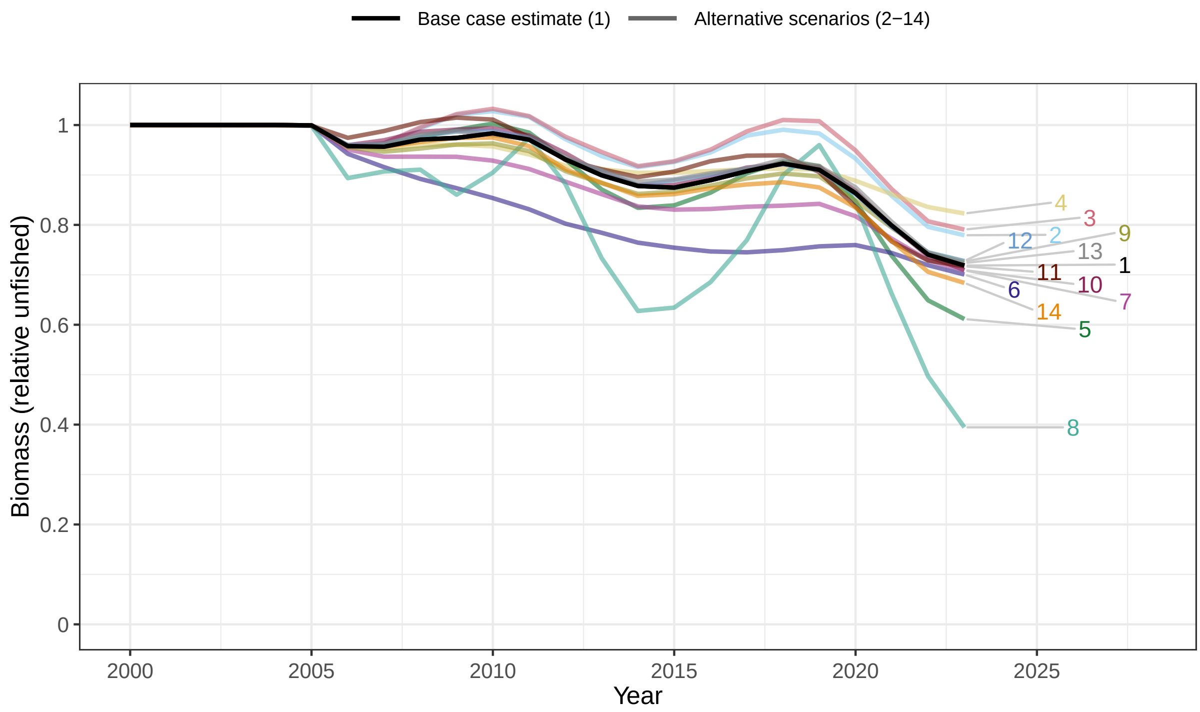


Figure G.3: MCMC predicted biomass trajectory relative to unfished for the Gould stock, from 2000 to 2023 for all Stock Synthesis model scenarios.

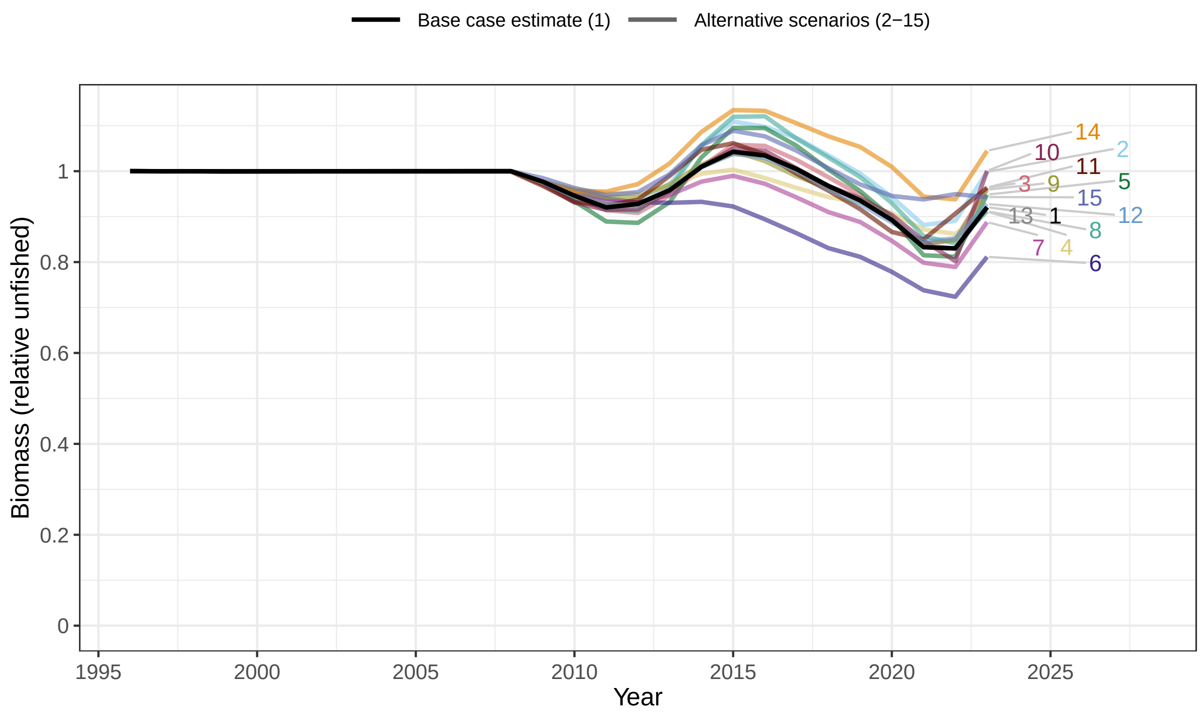


Figure G.4: MCMC predicted biomass trajectory relative to unfished for the Bunker stock, from 1996 to 2023 for all Stock Synthesis model scenarios.

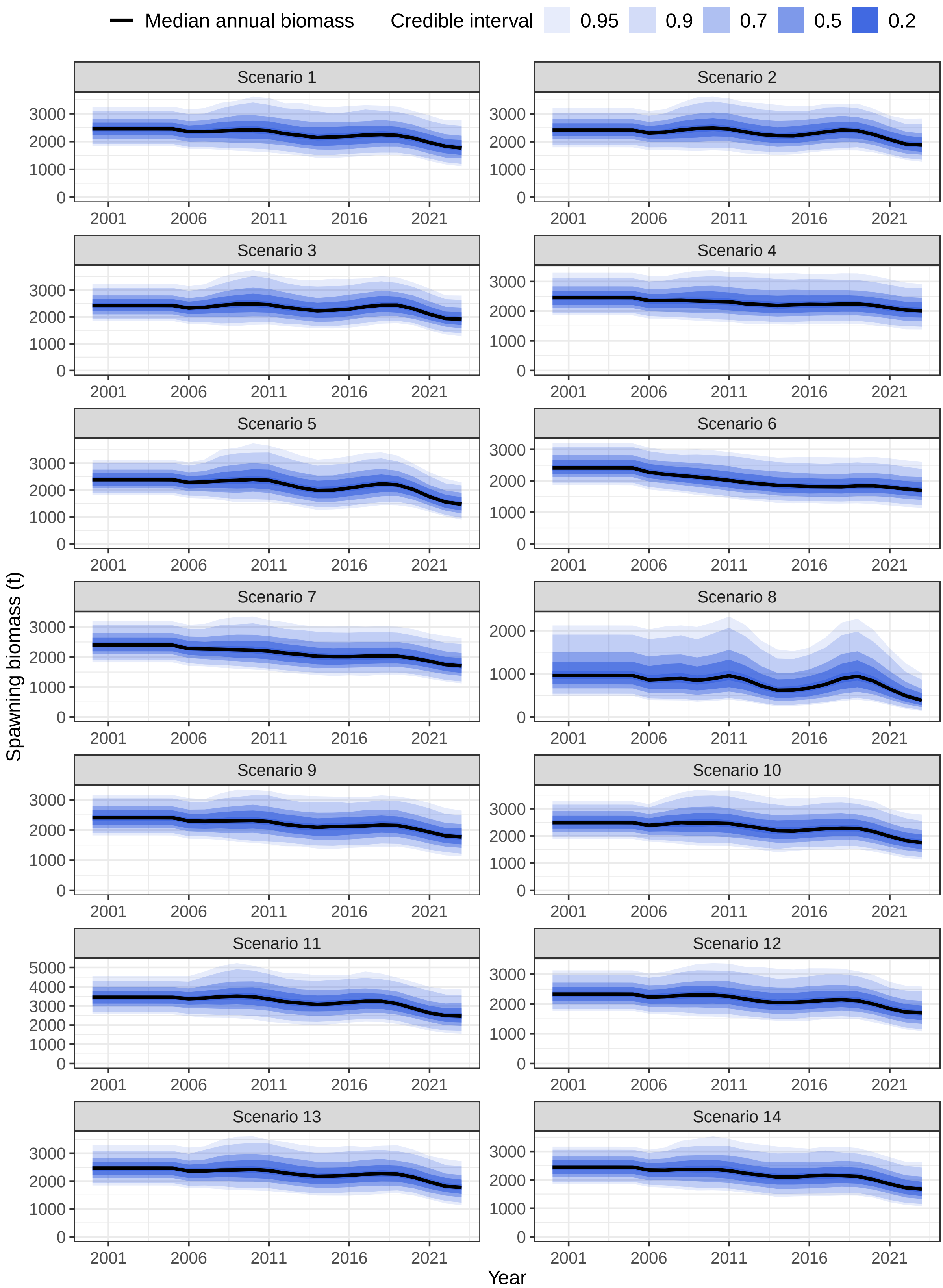


Figure G.5: MCMC predicted biomass trajectory relative to unfished from the Stock Synthesis model for the Gould stock, from 2000 to 2023. Blue shading indicates the biomass Bayesian credibility interval.

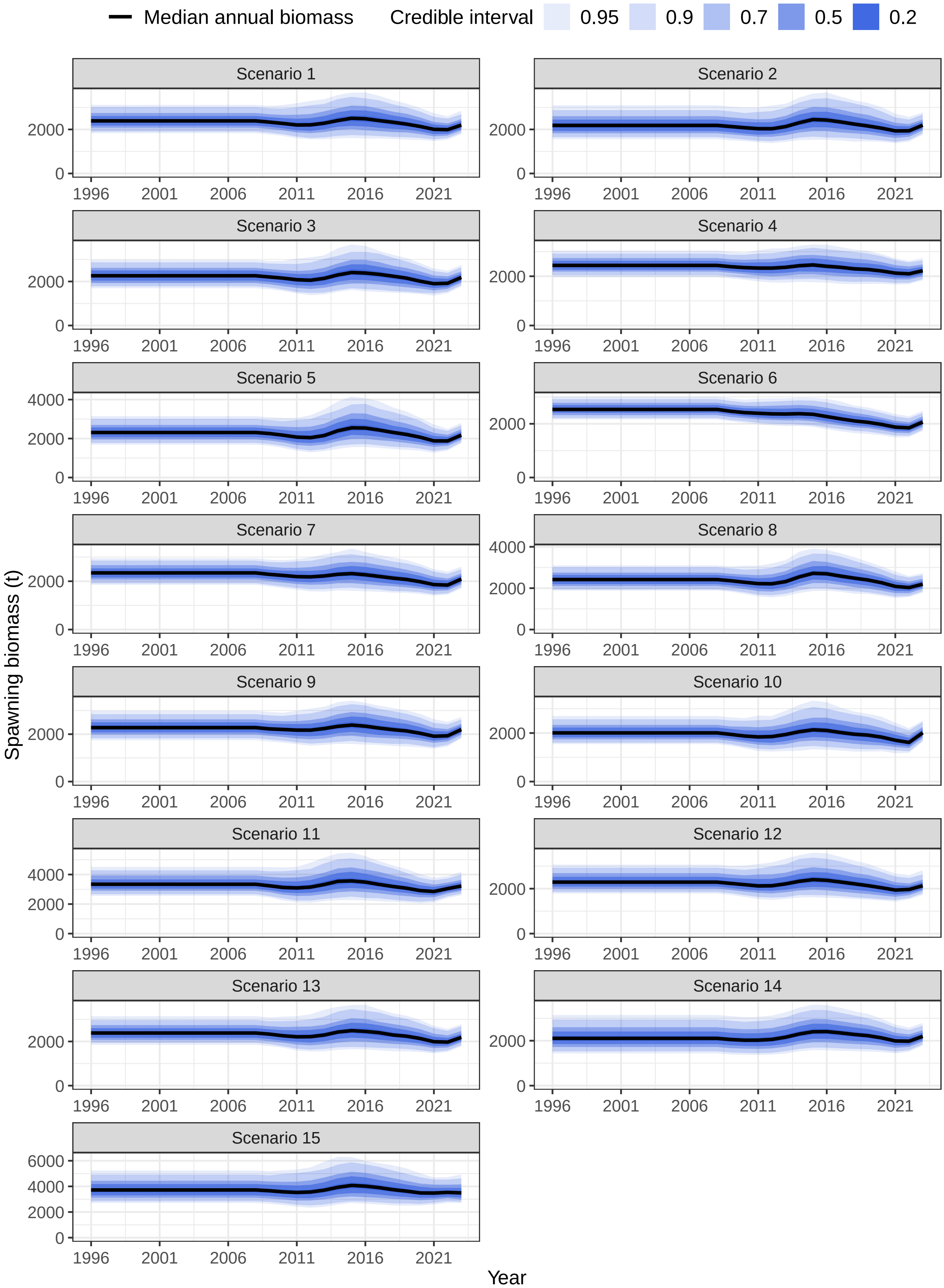


Figure G.6: MCMC predicted biomass trajectory relative to unfished from the Stock Synthesis model for the Bunker stock, from 1996 to 2023. Blue shading indicates the biomass Bayesian credibility interval.

G.3 Abundance indices

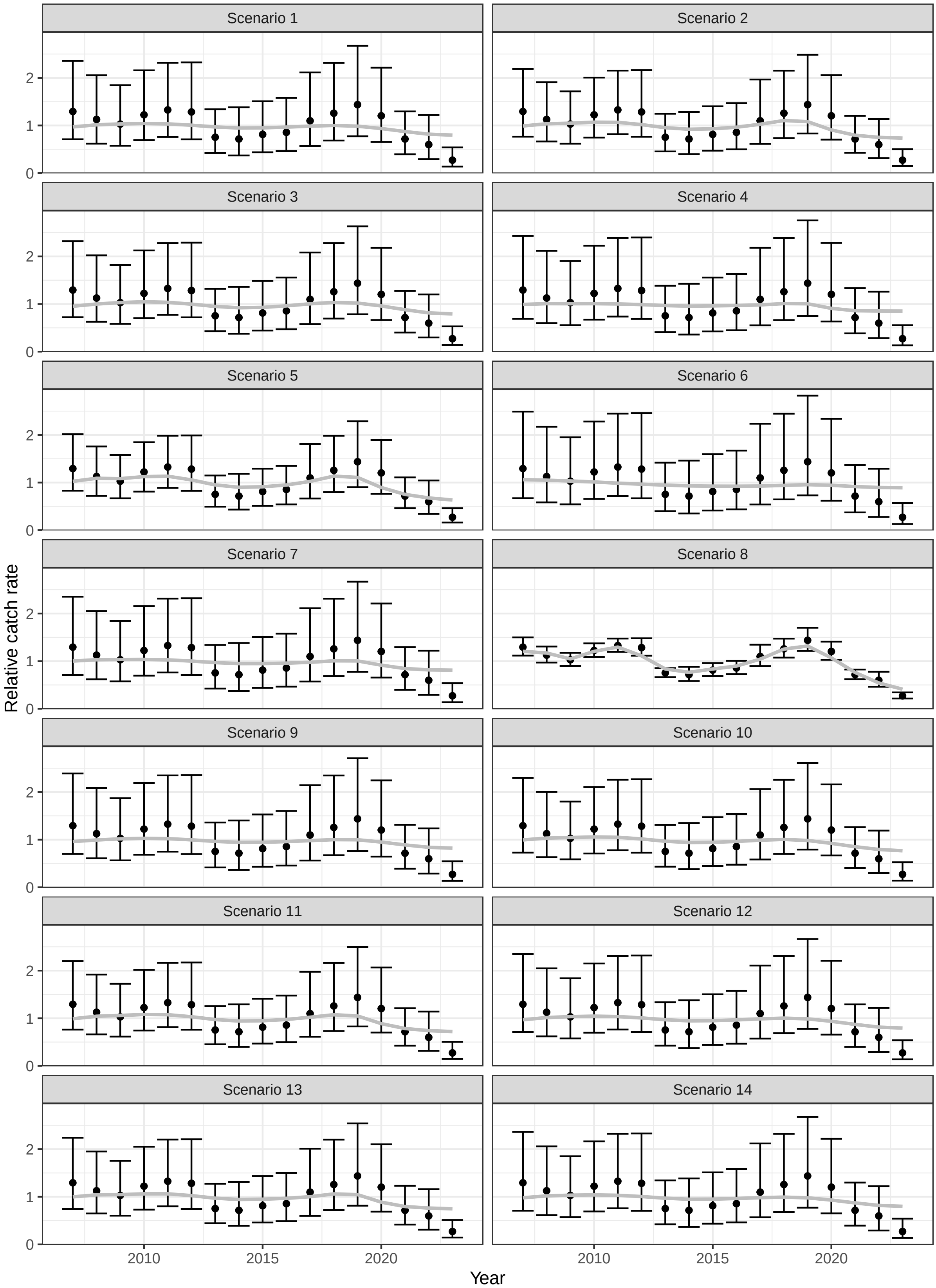


Figure G.7: Stock Synthesis model predictions (grey line) to commercial catch rates for the Gould stock, from 2007 to 2023 for each Stock Synthesis sensitivity scenario.

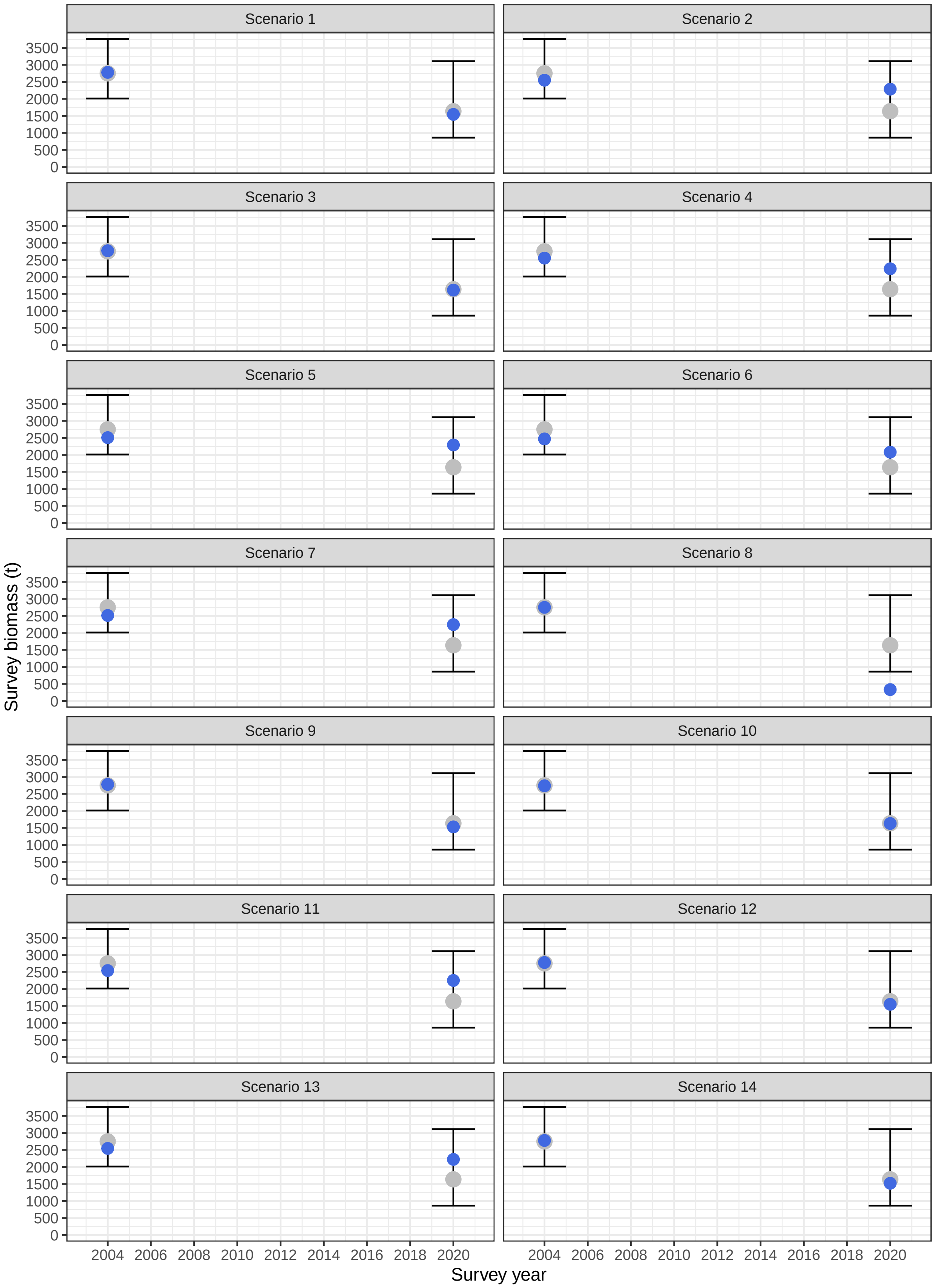


Figure G.8: Stock Synthesis model fit (blue dot) to survey estimated biomass (grey point with black error bars indicating the 95 percent CI of the estimate) for the Gould stock for each Stock Synthesis sensitivity scenario.

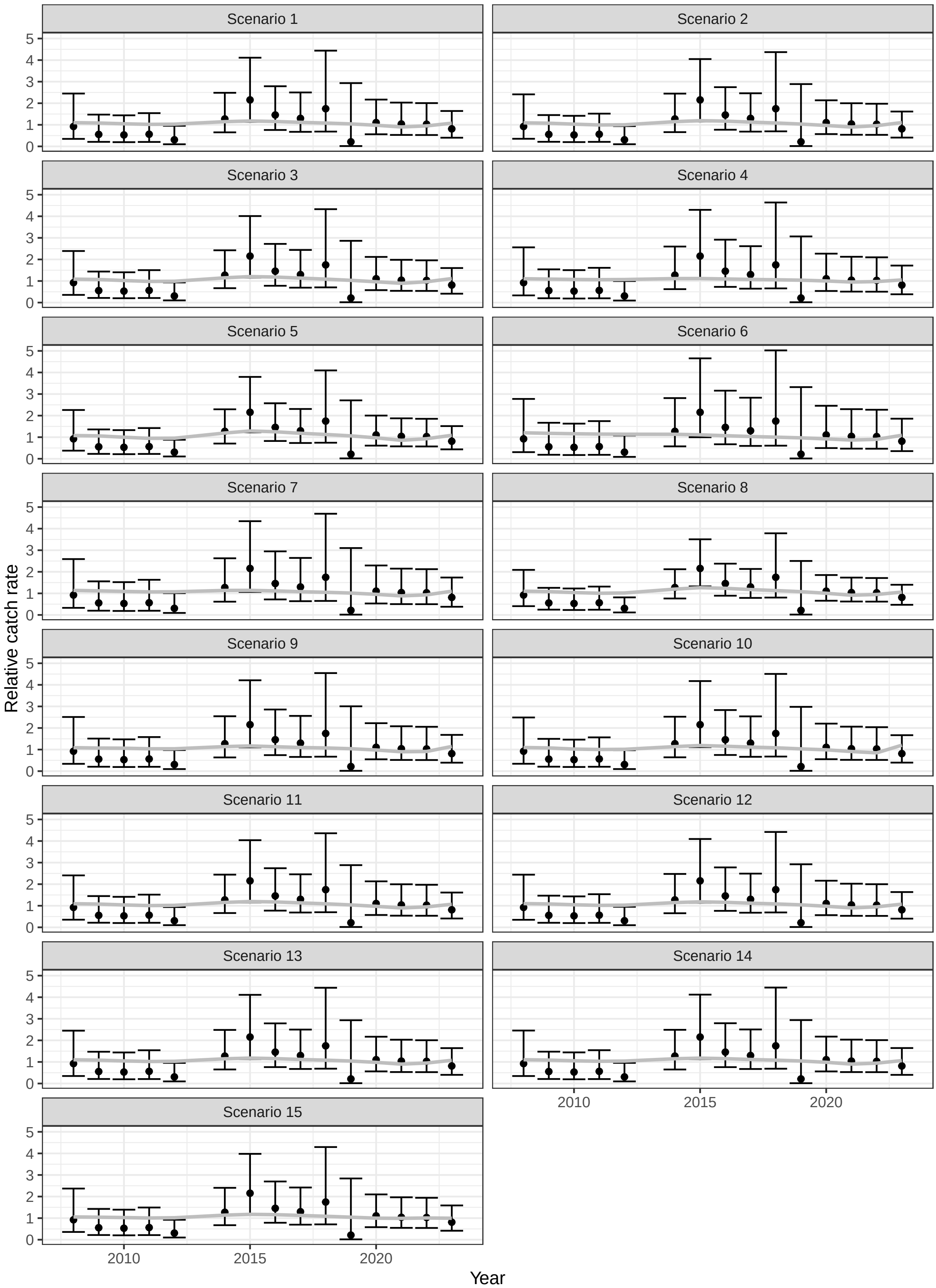


Figure G.9: Stock Synthesis model predictions (blue line) to commercial catch rates for the Bunker stock, from 2008 to 2023 for each Stock Synthesis sensitivity scenario.

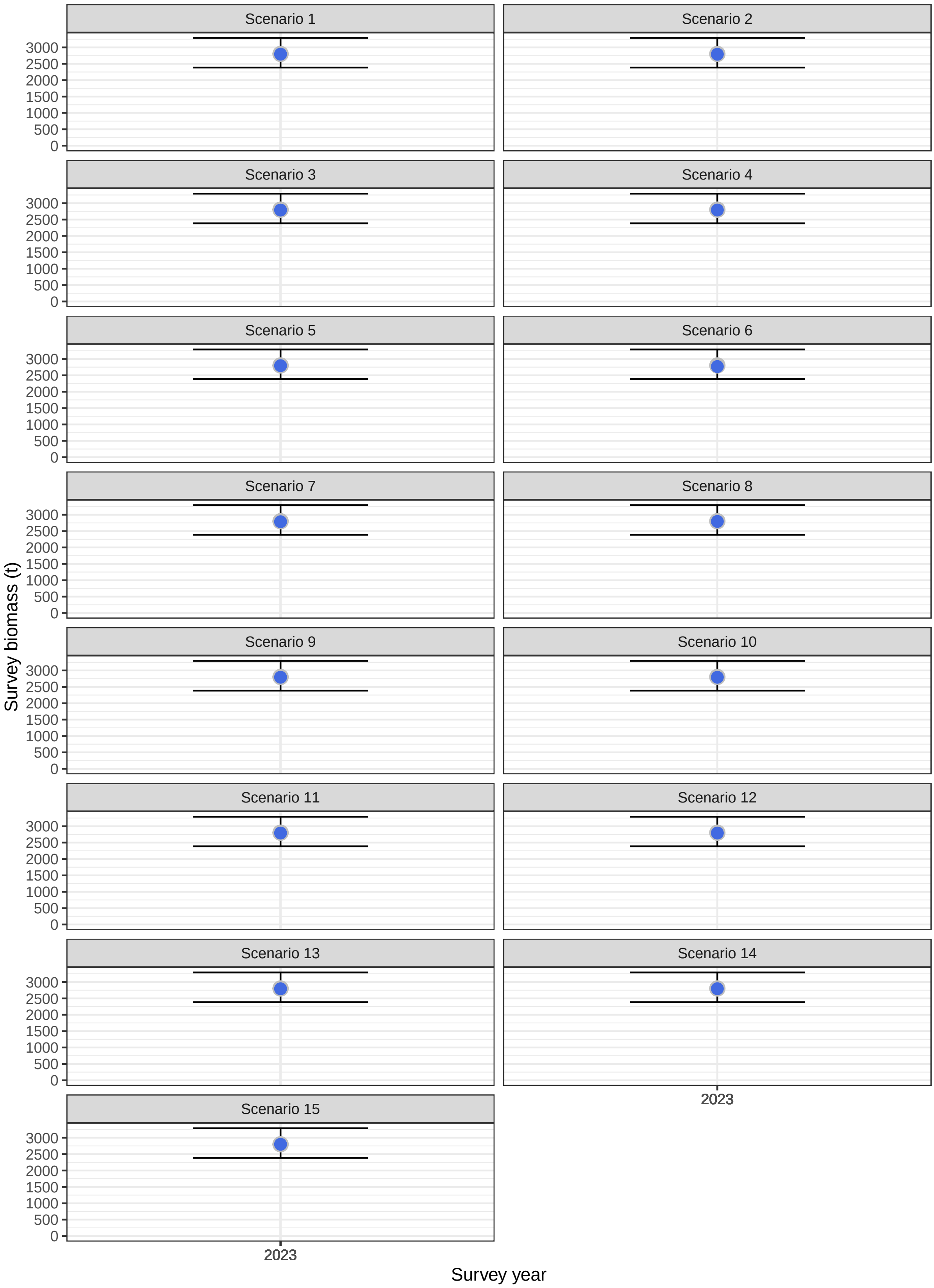


Figure G.10: Stock Synthesis model fit (blue dot) to survey estimated biomass (grey point with black error bars indicating the 95 percent CI of the estimate) for the Bunker stock for each Stock Synthesis sensitivity scenario.

G.4 Length composition

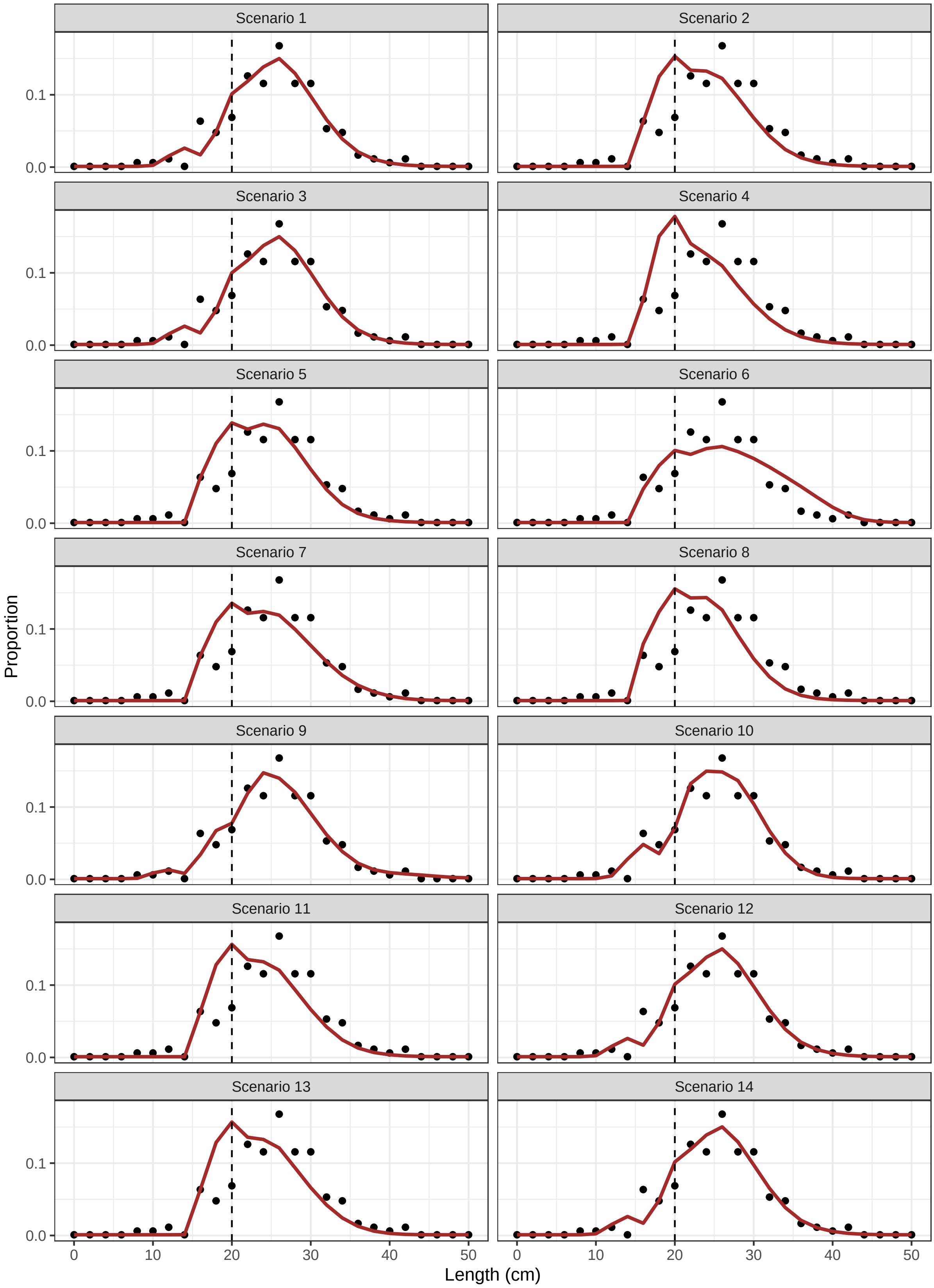


Figure G.11: Fits to length structures (brown line) for the 2020 survey for the Gould stock for each Stock Synthesis sensitivity scenario. The dashed vertical line indicates the MLS of 20 cm.

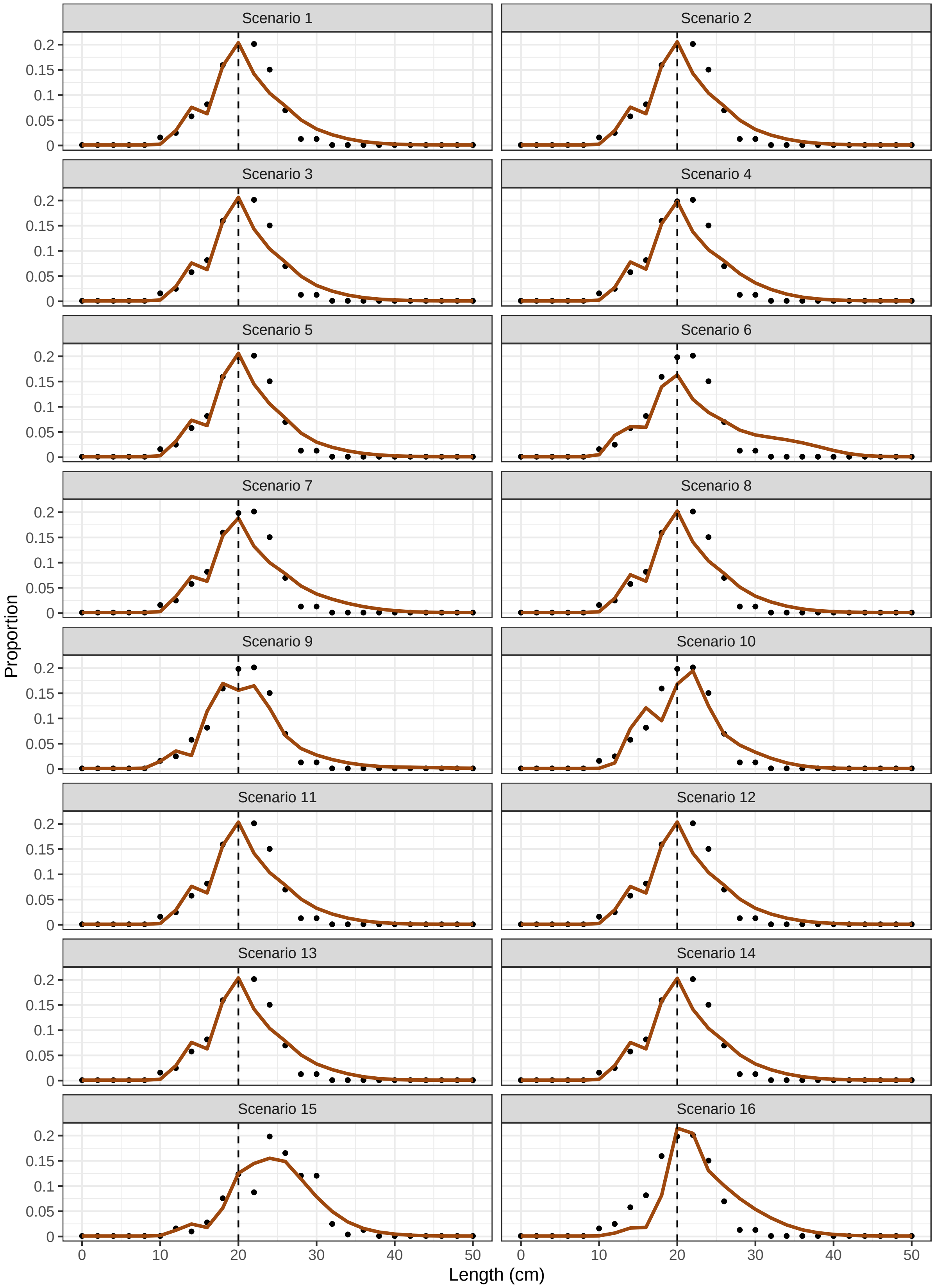


Figure G.12: Stock Synthesis model fit (brown line) to length structures for the 2023 survey for the Bunker stock for each Stock Synthesis sensitivity scenario. The dashed vertical line indicates the MLS of 20 cm.

G.5 Stock Recruitment curve

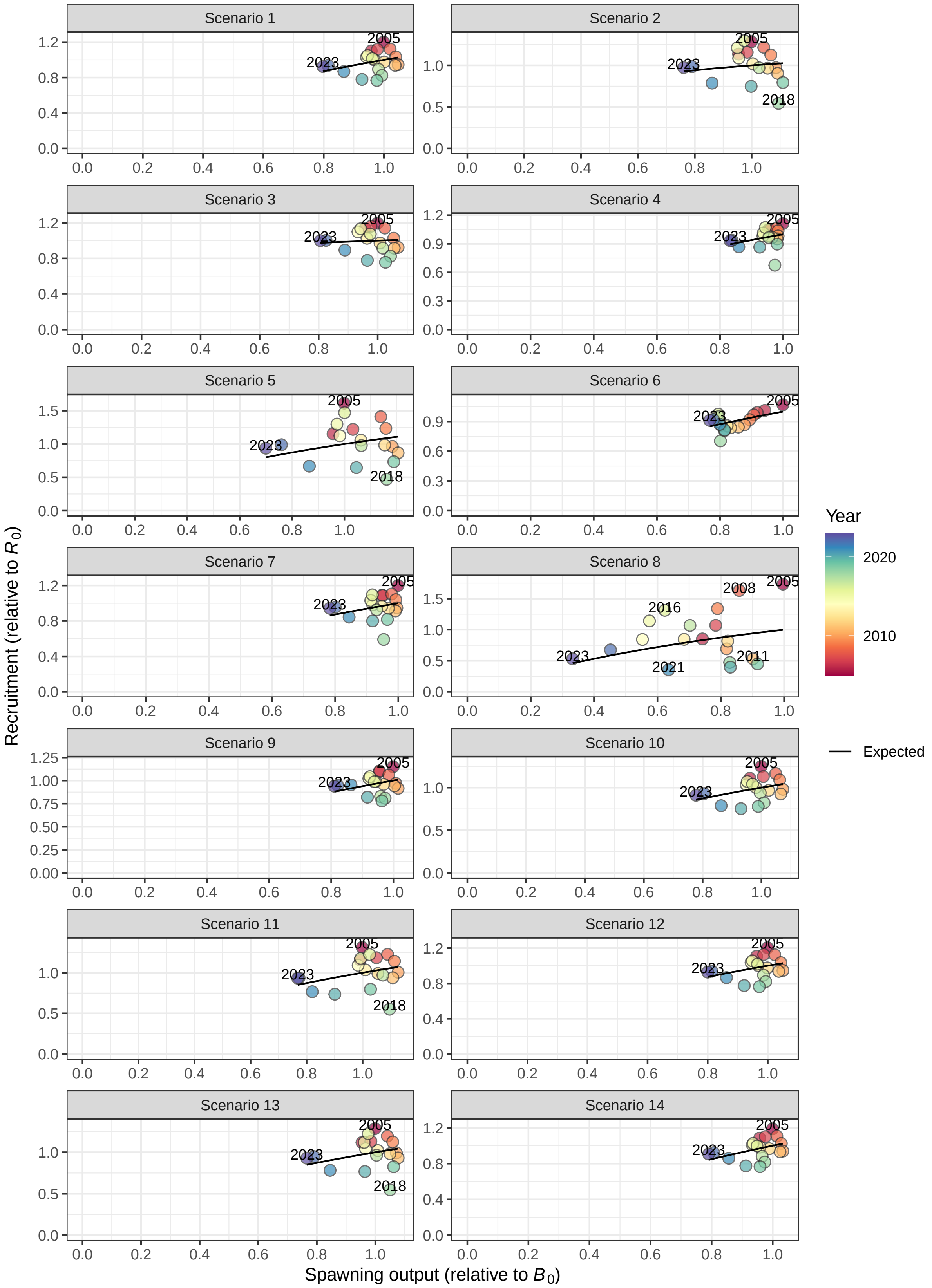


Figure G.13: Stock-recruitment curve for each Stock Synthesis sensitivity scenario conducted for the Gould stock. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

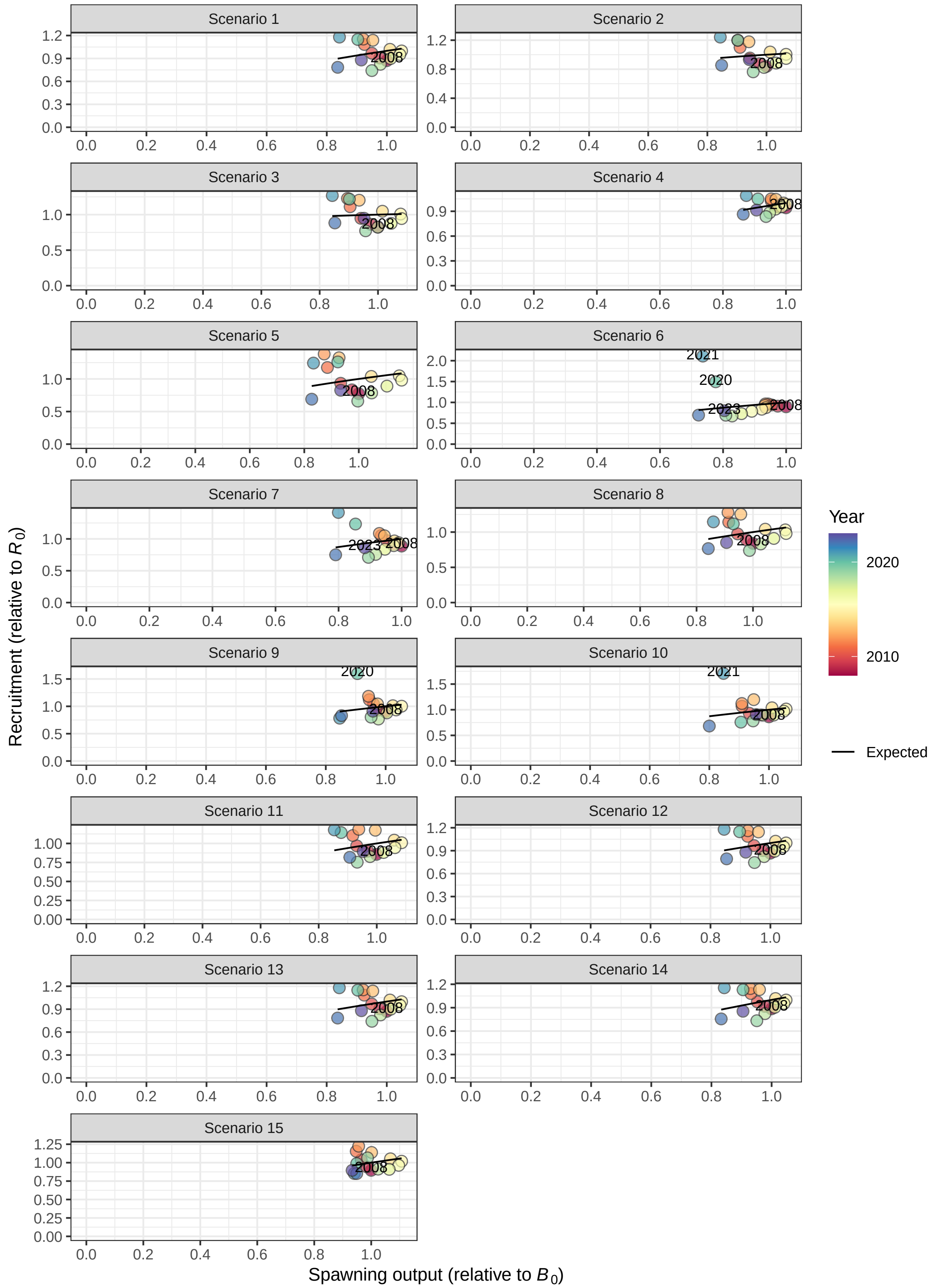


Figure G.14: Stock-recruitment curve for each Stock Synthesis sensitivity scenario conducted for the Bunker stock. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

G.6 Recruitment deviations

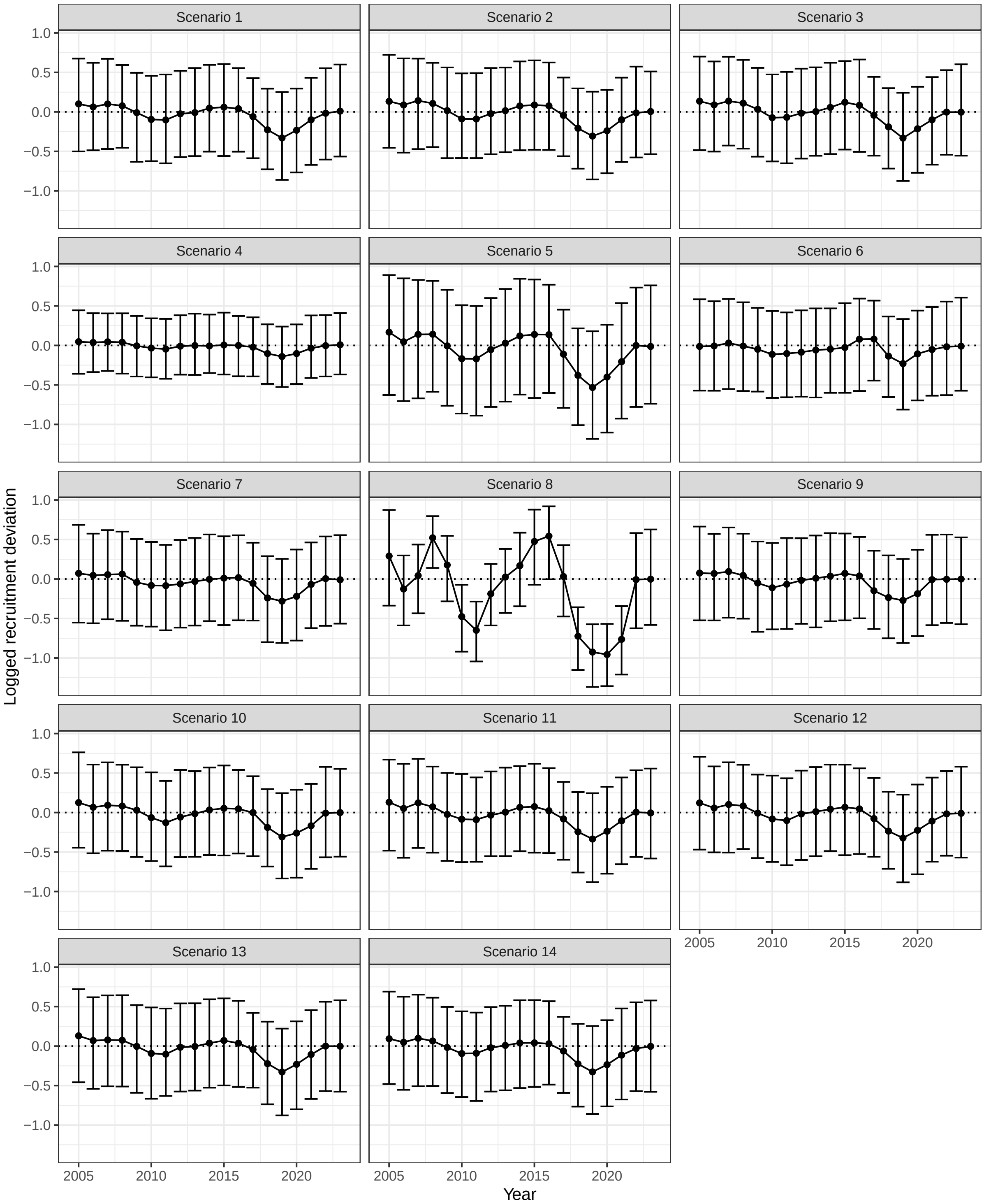


Figure G.15: Recruitment deviations for each Stock Synthesis sensitivity scenario conducted for the Gould stock, from 2005 to 2023.

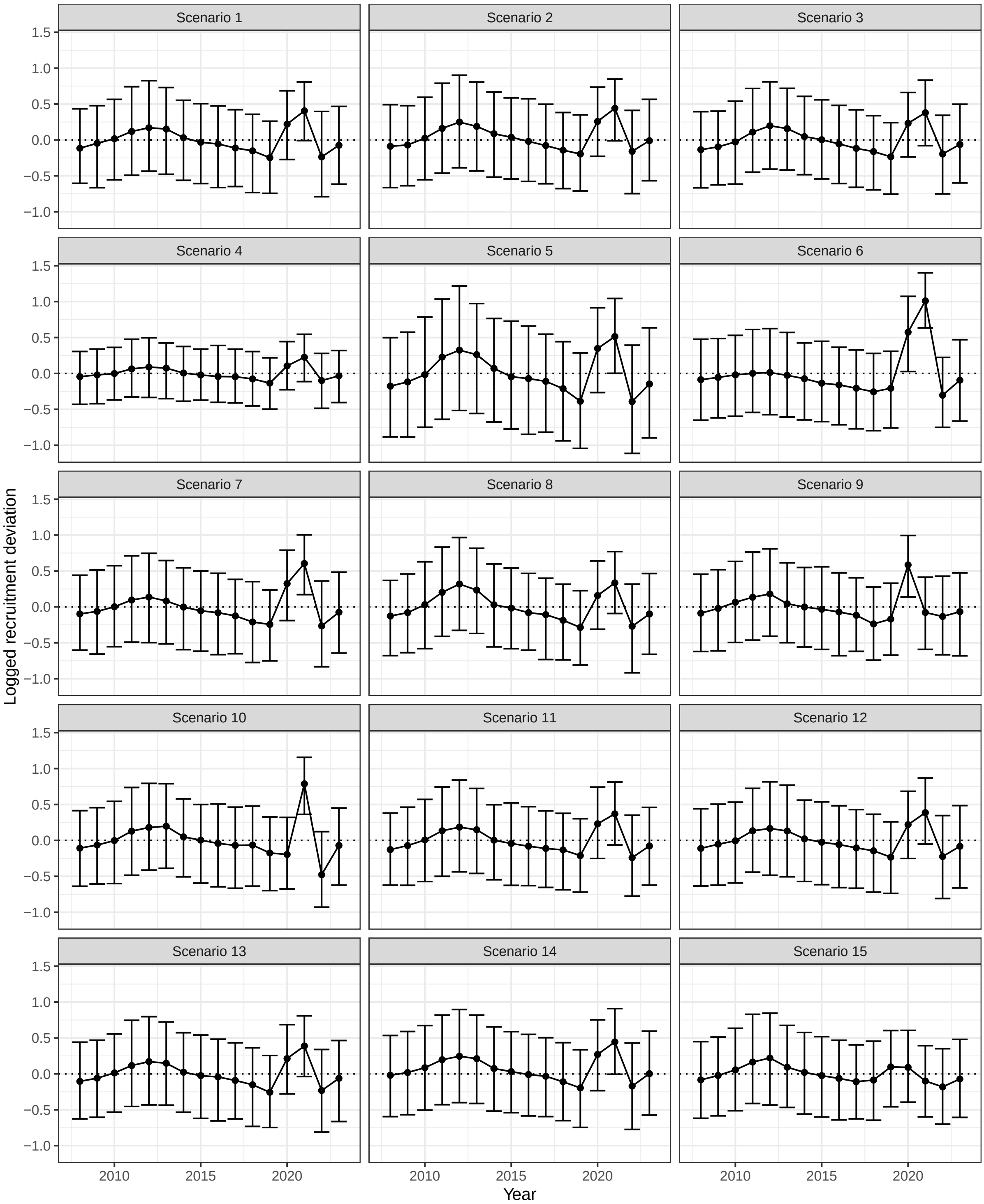


Figure G.16: Recruitment deviations for each Stock Synthesis sensitivity scenario conducted for the Bunker stock, from 2008 to 2023.

G.7 Fishing mortality

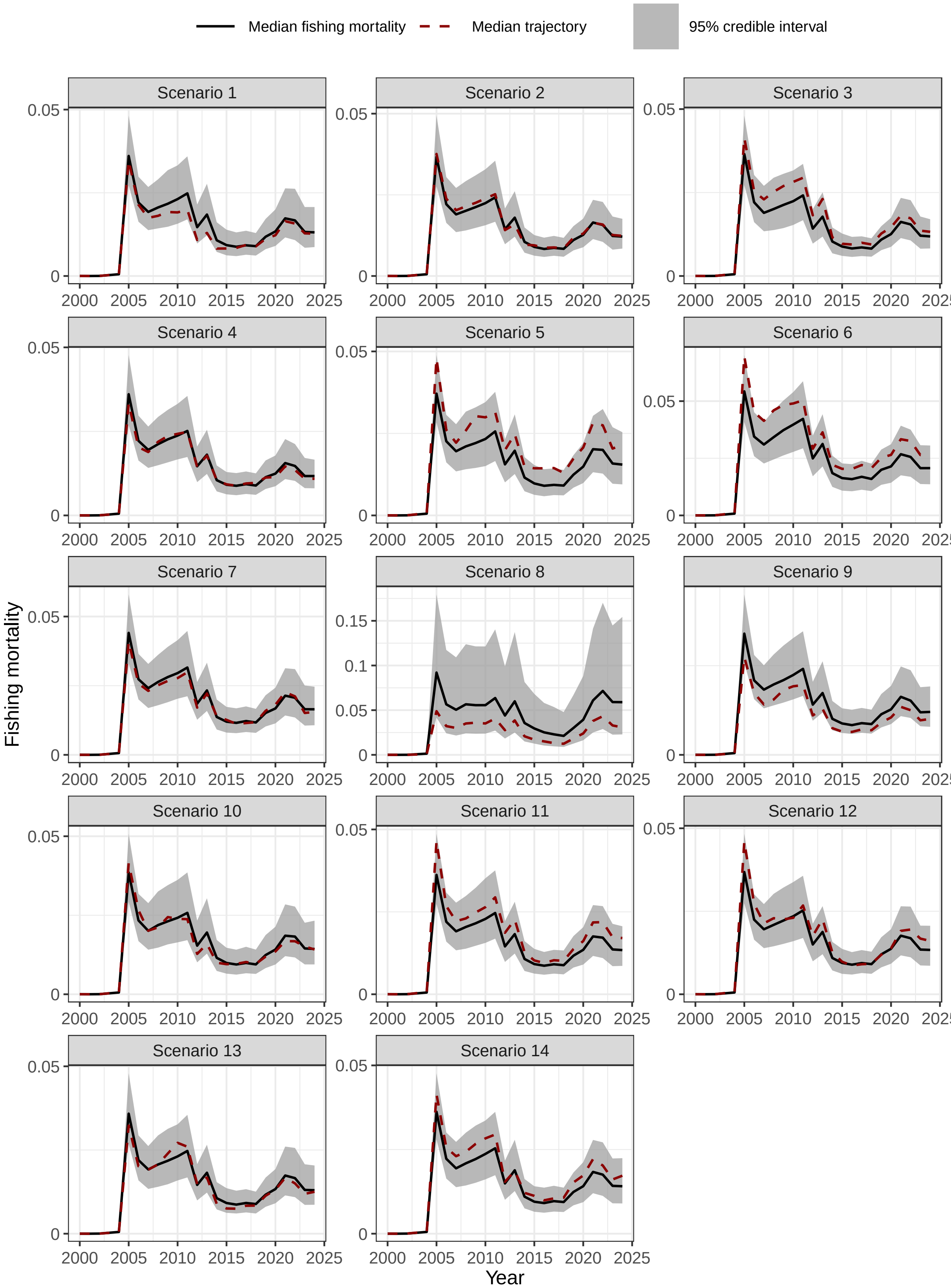


Figure G.17: Predicted fishing mortality (F) for the legal-size biomass for each Stock Synthesis sensitivity scenario conducted for the Gould stock, from 2000 to 2023

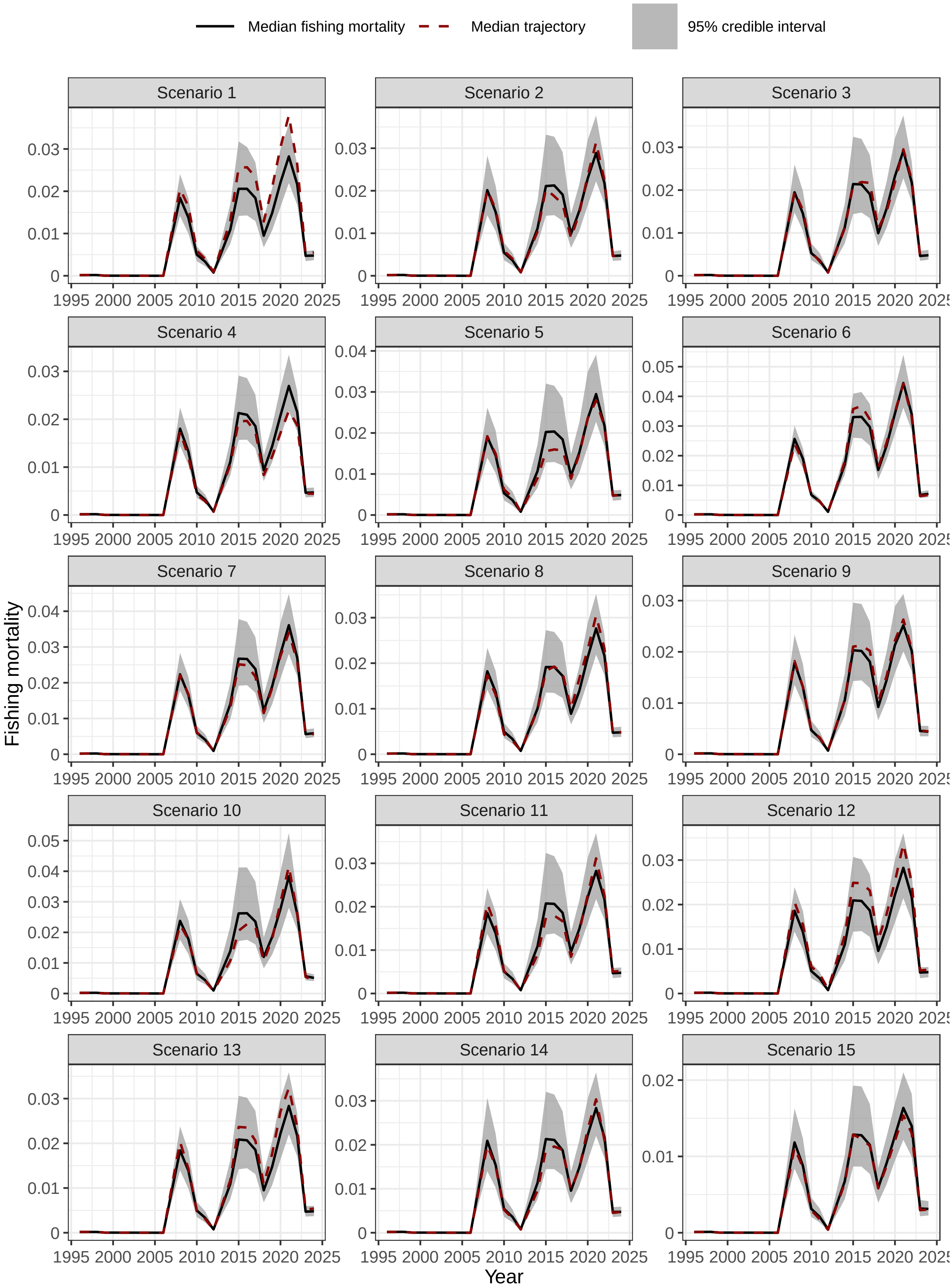


Figure G.18: Predicted fishing mortality (F) for the legal-size biomass for each Stock Synthesis sensitivity scenario conducted for the Bunker stock, from 1996 to 2023

Appendix H DDUST Scenario outputs

H.1 Sensitivity

Table H.1: Scenarios tested to determine sensitivity to parameters, assumptions and model inputs

Scenario	Stocks	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	Slower growth
10	All	Faster growth

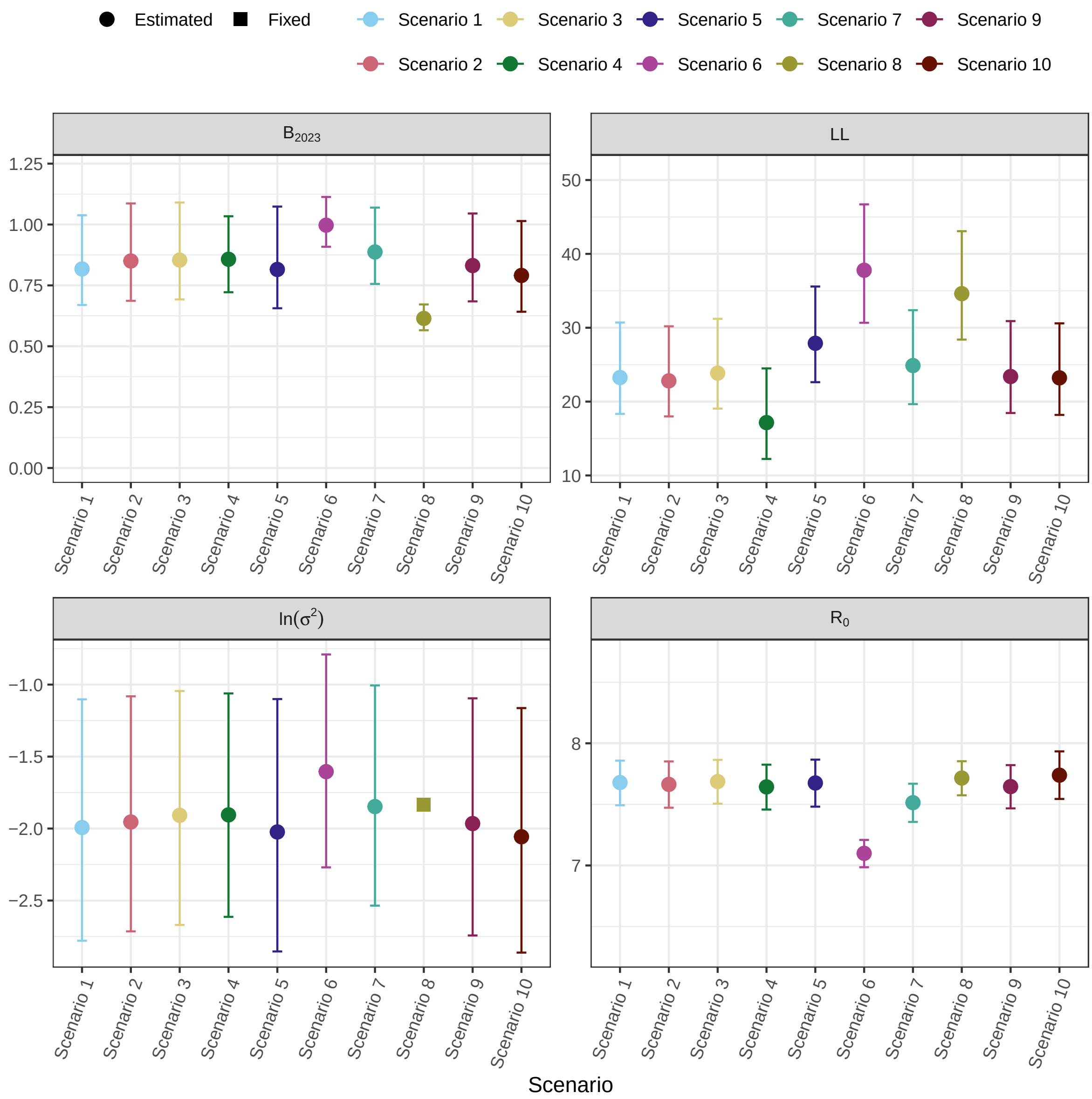


Figure H.1: DDUST sensitivity plots of estimated parameters for the Gould stock.

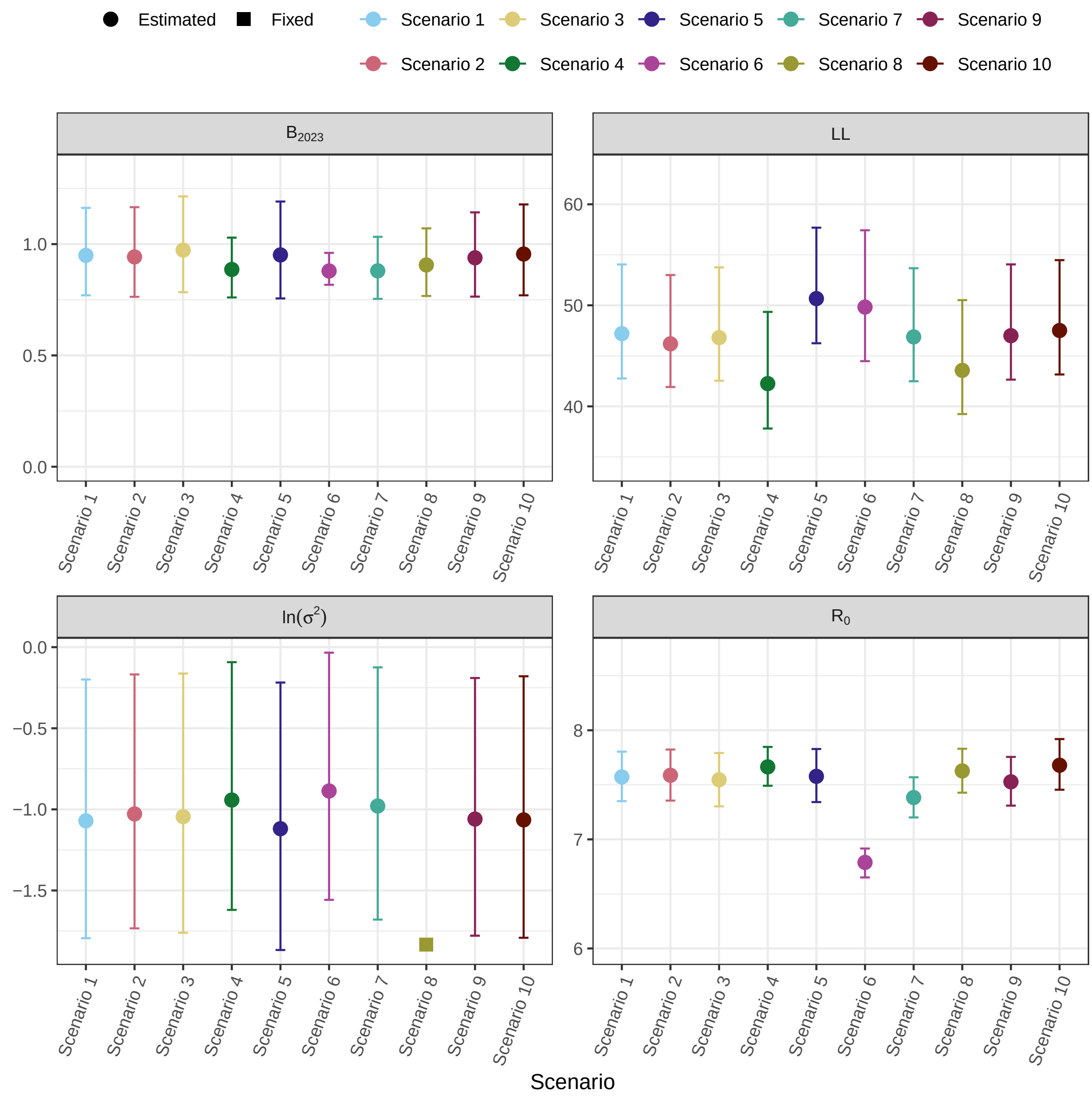


Figure H.2: DDUST sensitivity plots of estimated parameters for the Bunker stock.

H.2 Biomass

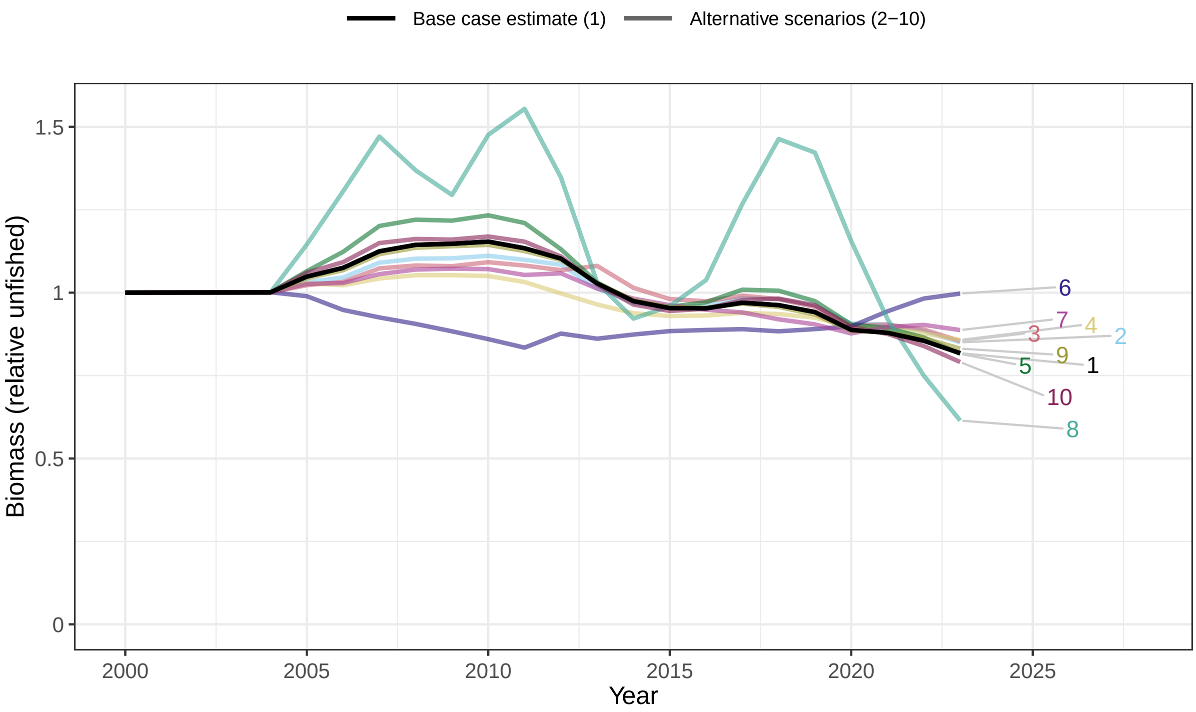


Figure H.3: MCMC predicted biomass trajectory relative to unfished for the Gould stock, from 2000 to 2023 for all DDUST model scenarios.

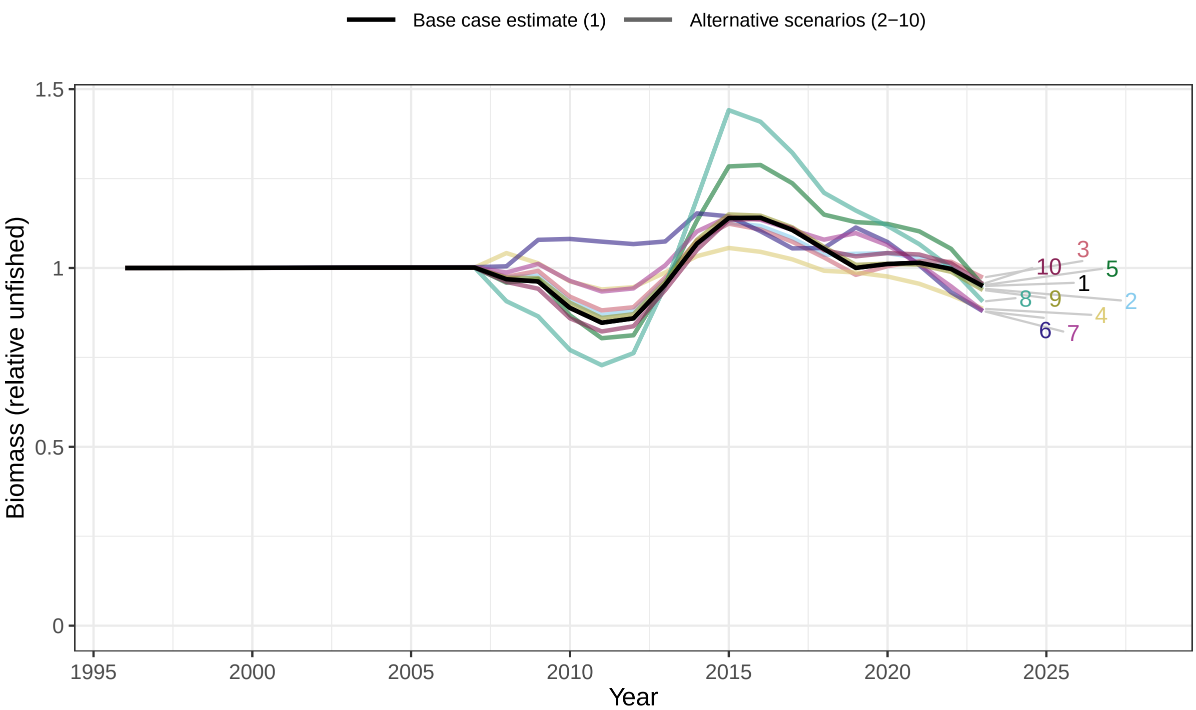


Figure H.4: MCMC predicted biomass trajectory relative to unfished for the Bunker stock, from 1996 to 2023 for all DDUST model scenarios.

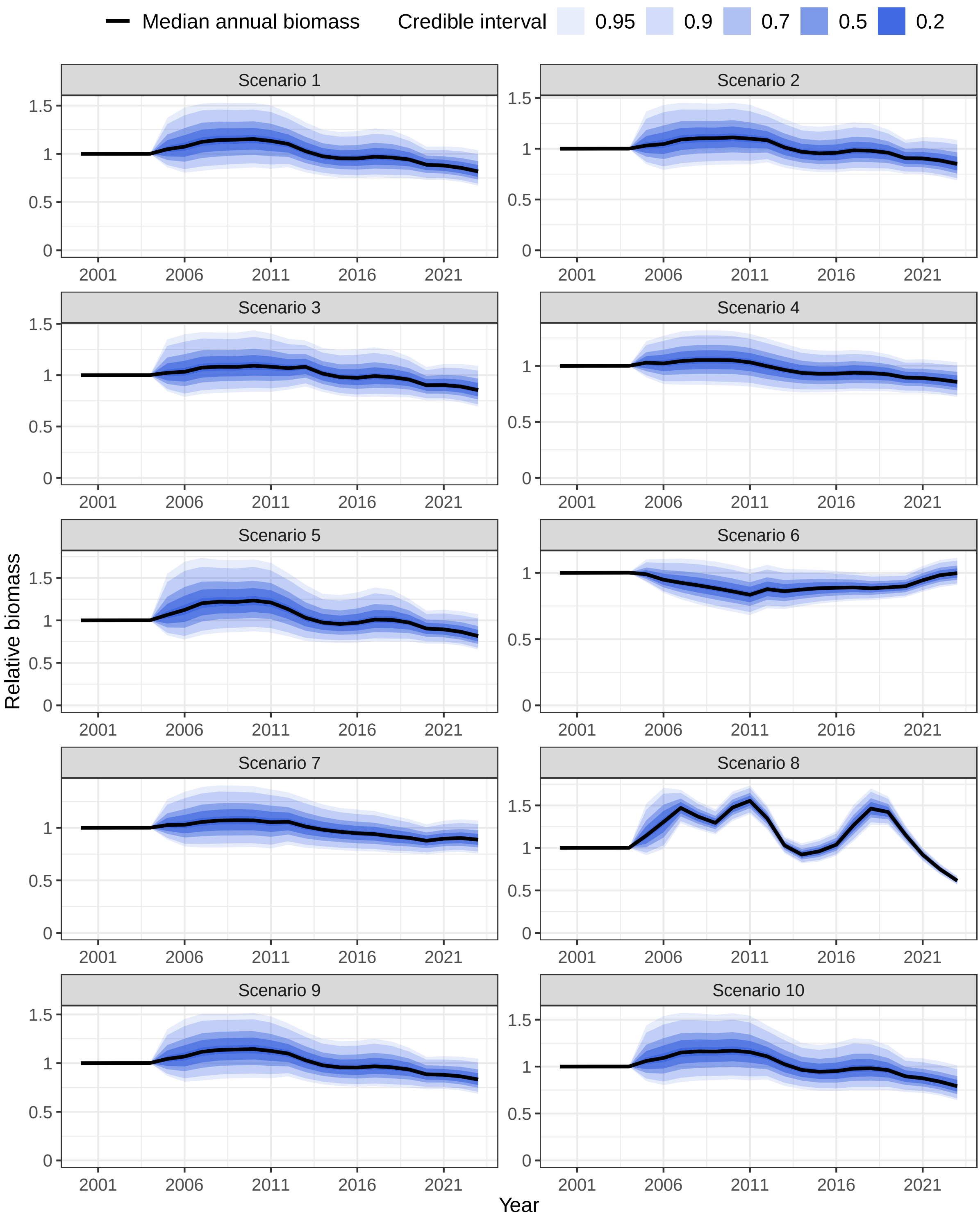


Figure H.5: MCMC predicted biomass trajectory relative to unfished from the DDUST model sensitivity scenarios for the Gould stock, from 1996 to 2023.

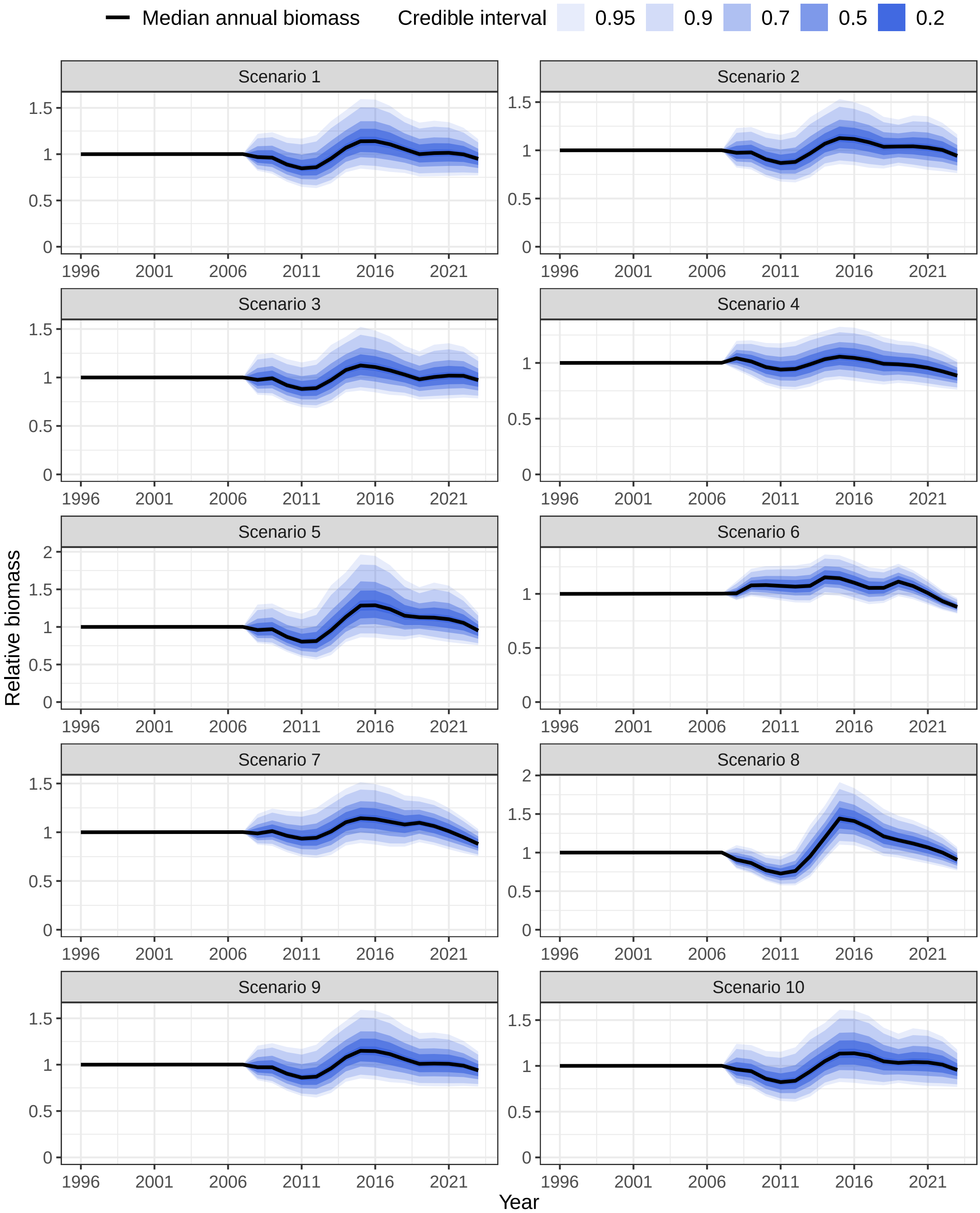


Figure H.6: MCMC predicted biomass trajectory relative to unfished from the DDUST model sensitivity scenarios for the Bunker stock, from 1996 to 2023.

H.3 Abundance indices

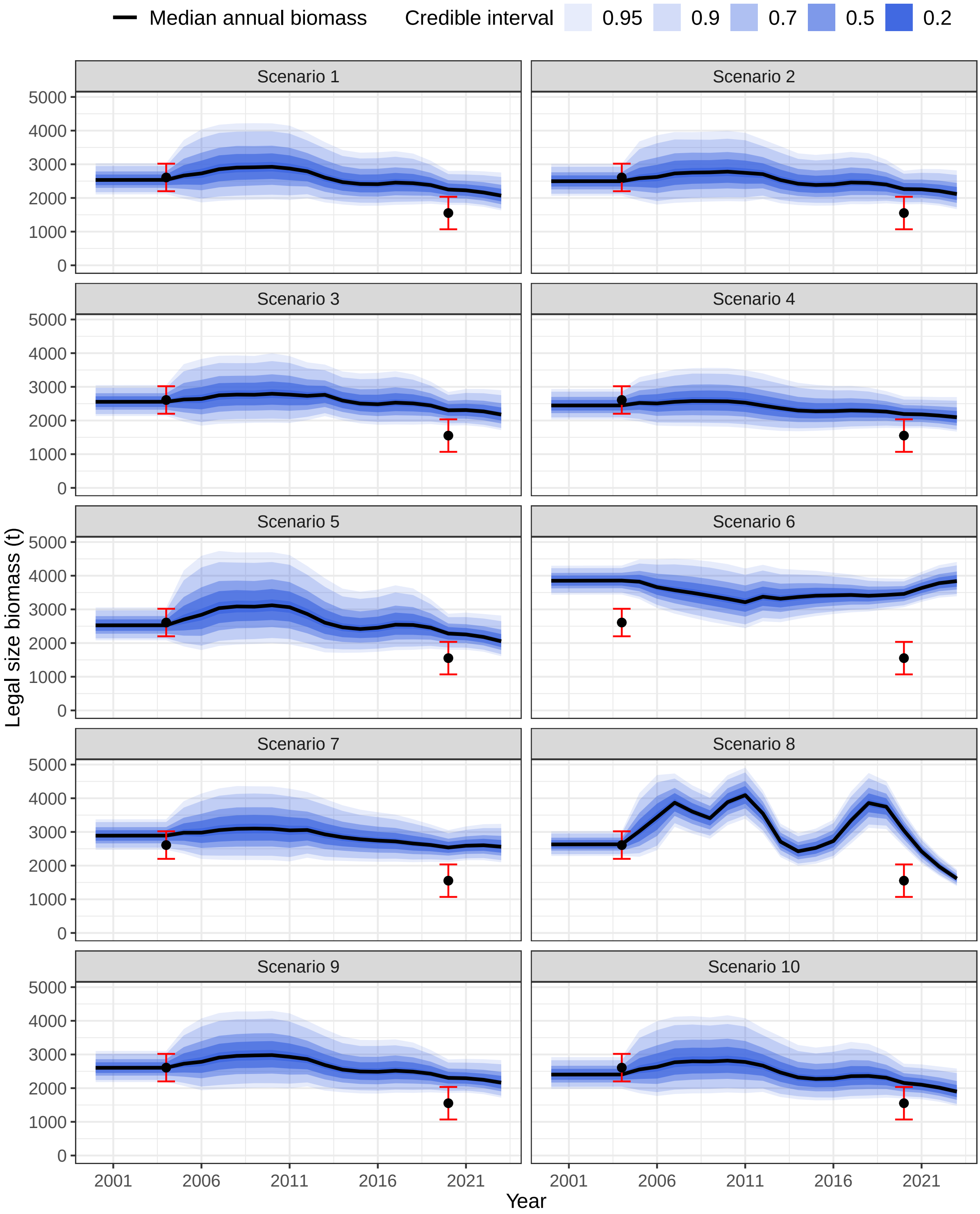


Figure H.7: Model fits to legal-sized biomass (black point with red error bars indicating the sd of the estimate) for the Gould stock, from 2000 to 2023 for each DDUST sensitivity scenario.

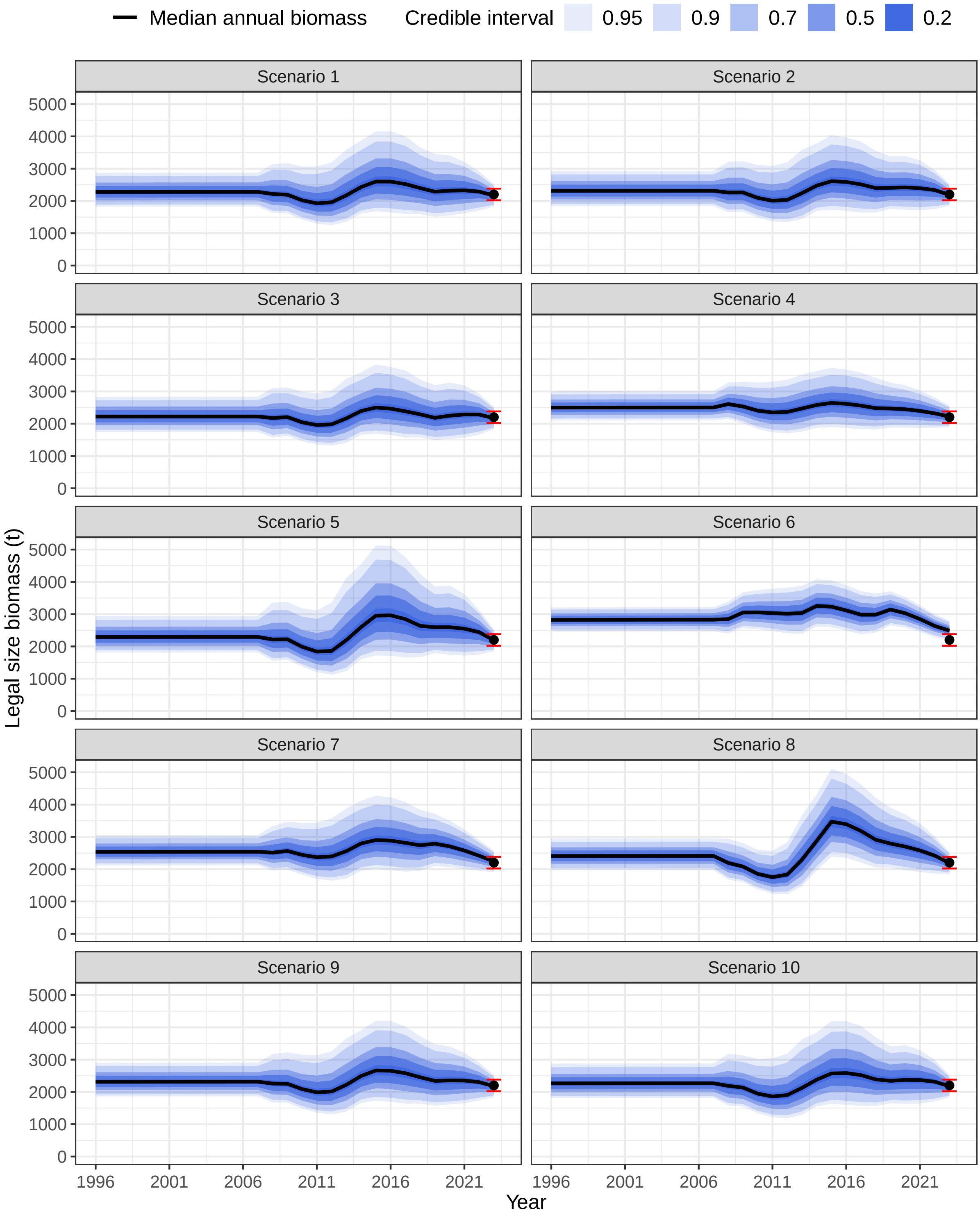


Figure H.8: Model fits to legal-sized biomass (black point with red error bars indicating the sd of the estimate) for the Bunker stock, from 1996 to 2023 for each DDUST sensitivity scenario.

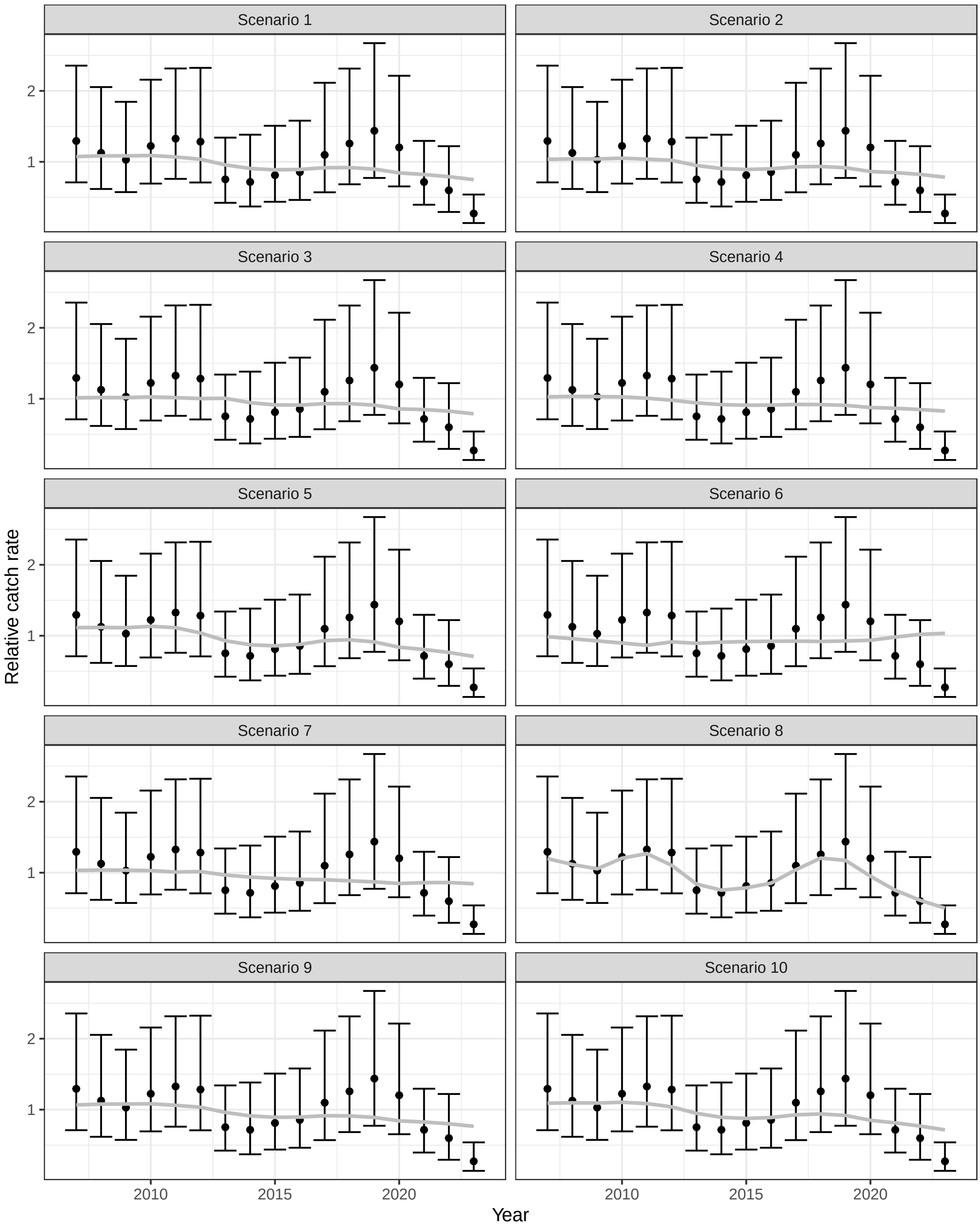


Figure H.9: Model predictions to commercial catch rates for the Gould stock, from 2007 to 2023 for each DDUST sensitivity scenario.

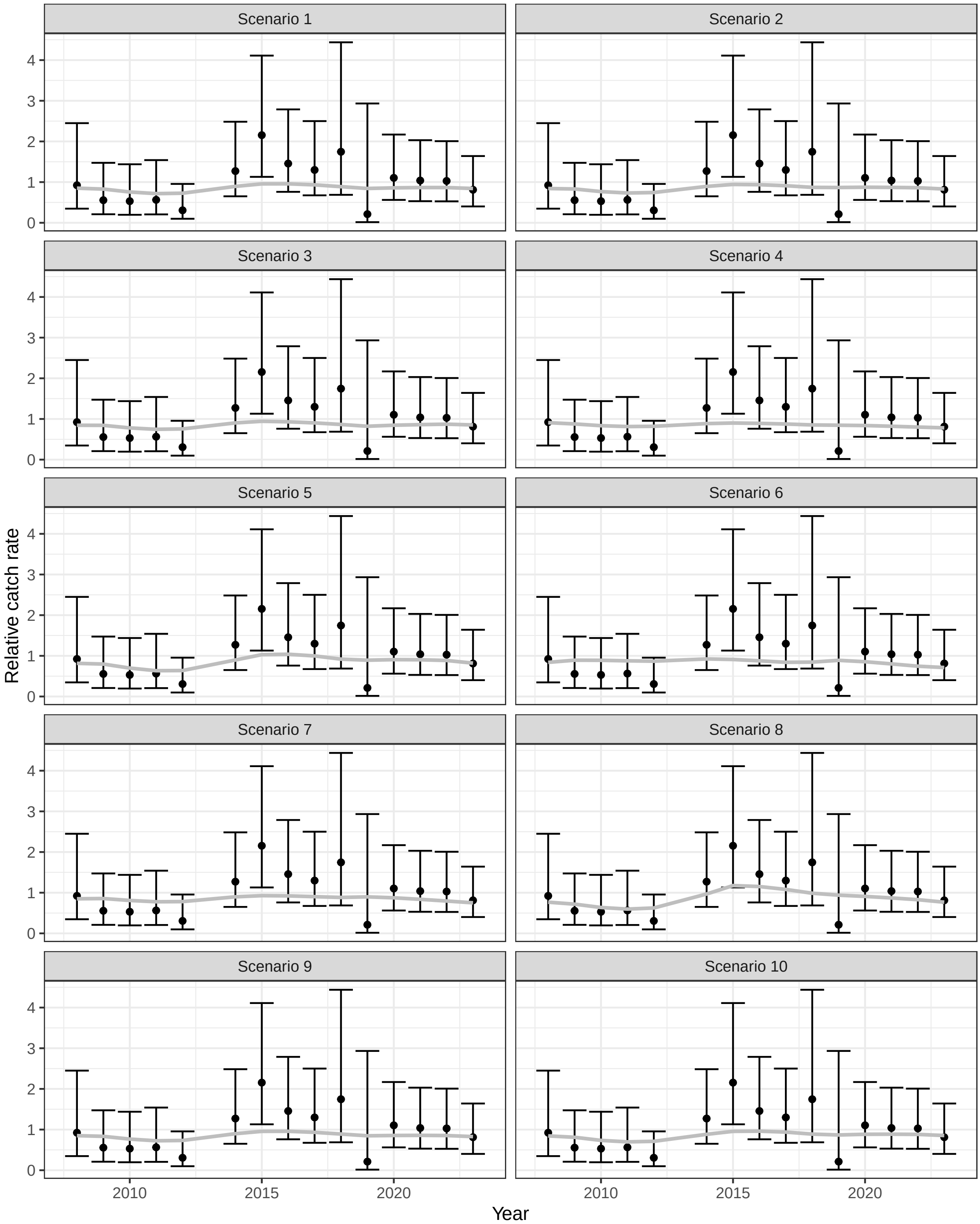


Figure H.10: Model predictions to commercial catch rates for the Bunker stock, from 2008 to 2023 for each DDUST sensitivity scenario.

H.4 Stock recruitment

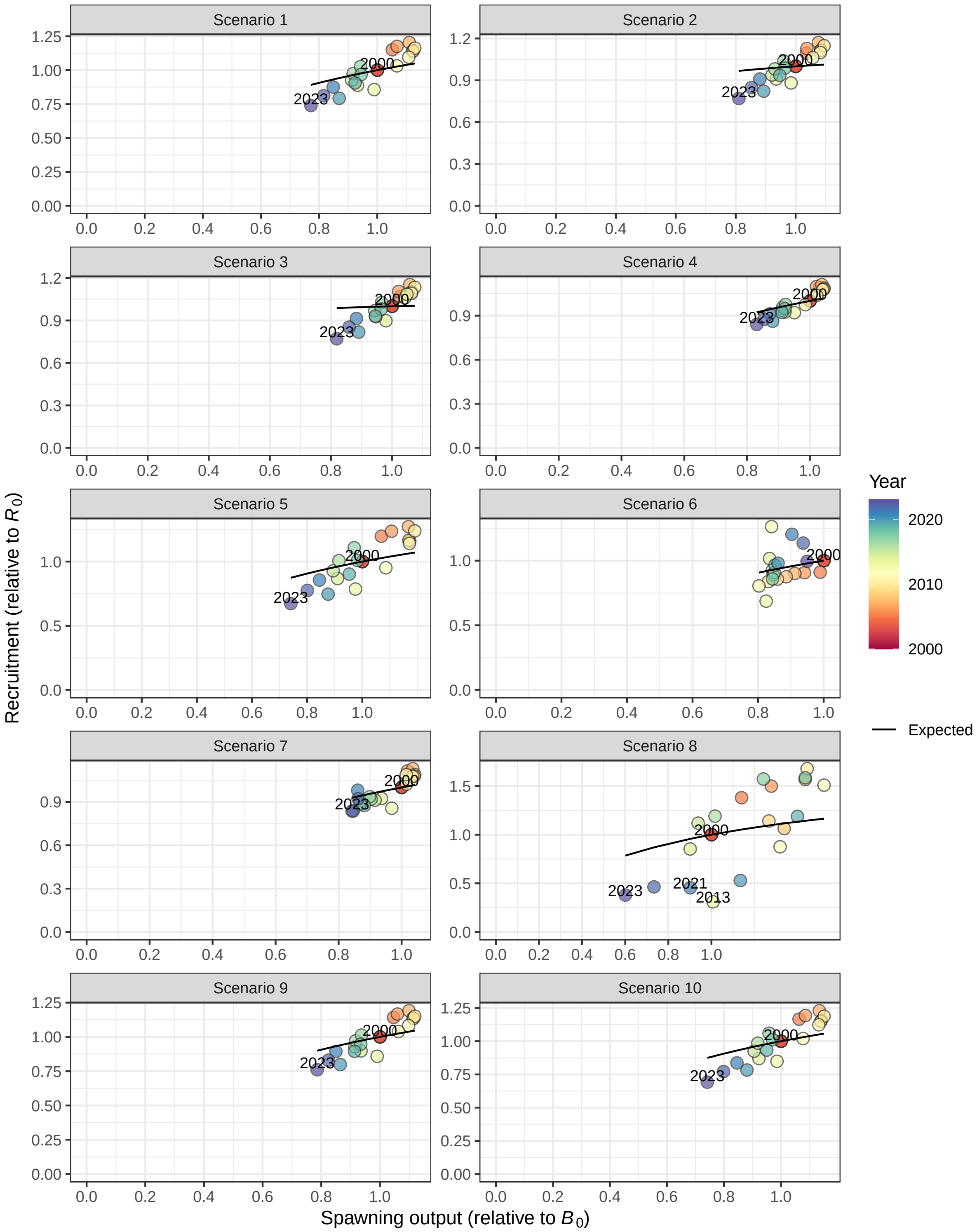


Figure H.11: Stock-recruitment curve for the eight sensitivity scenarios conducted for the Gould stock DDUST model. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

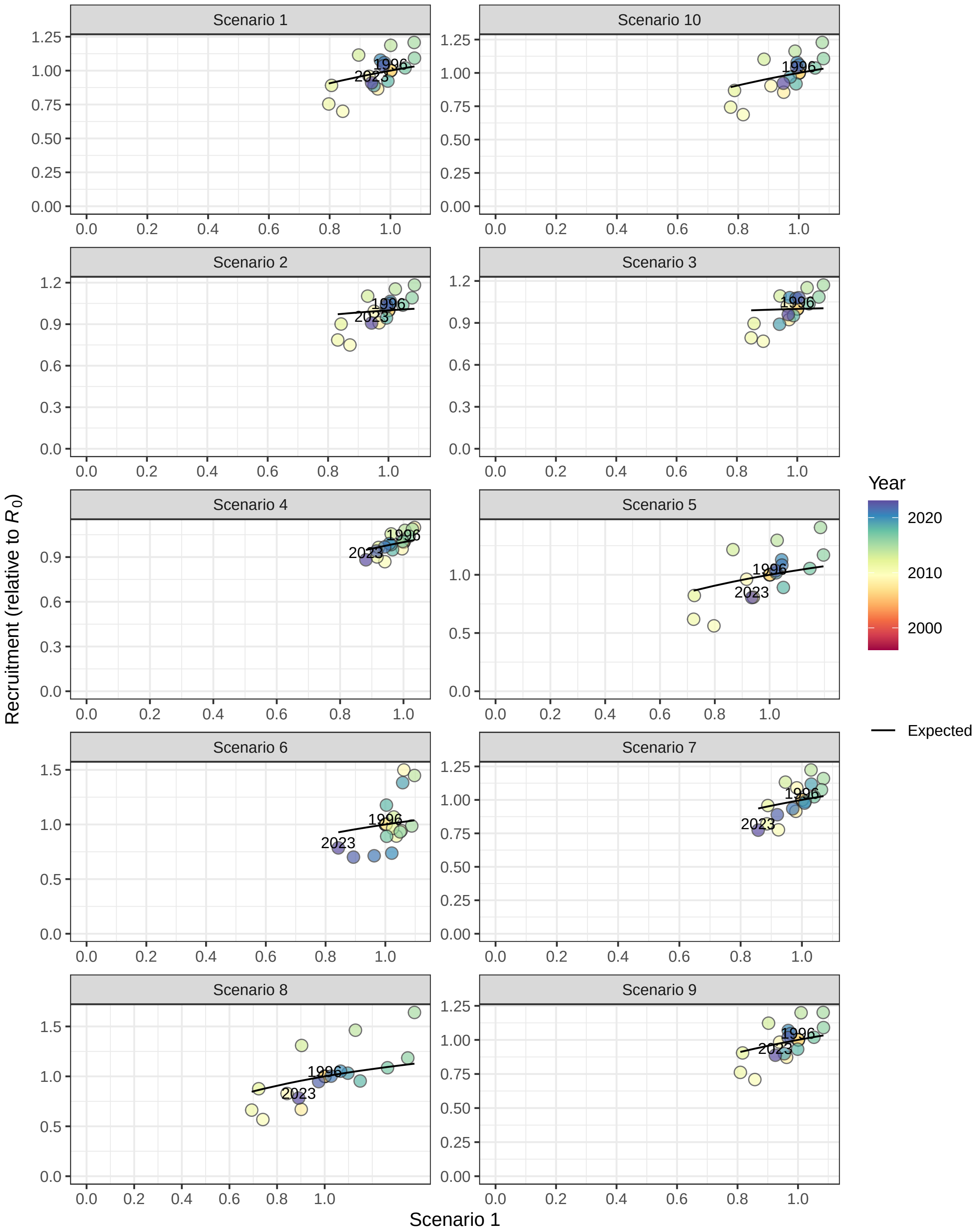


Figure H.12: Stock-recruitment curve for the eight sensitivity scenarios conducted for the Bunker stock DDUST model. Point colours indicate year, with warmer colours indicating earlier years and cooler colours in showing later years.

H.5 Recruitment deviations

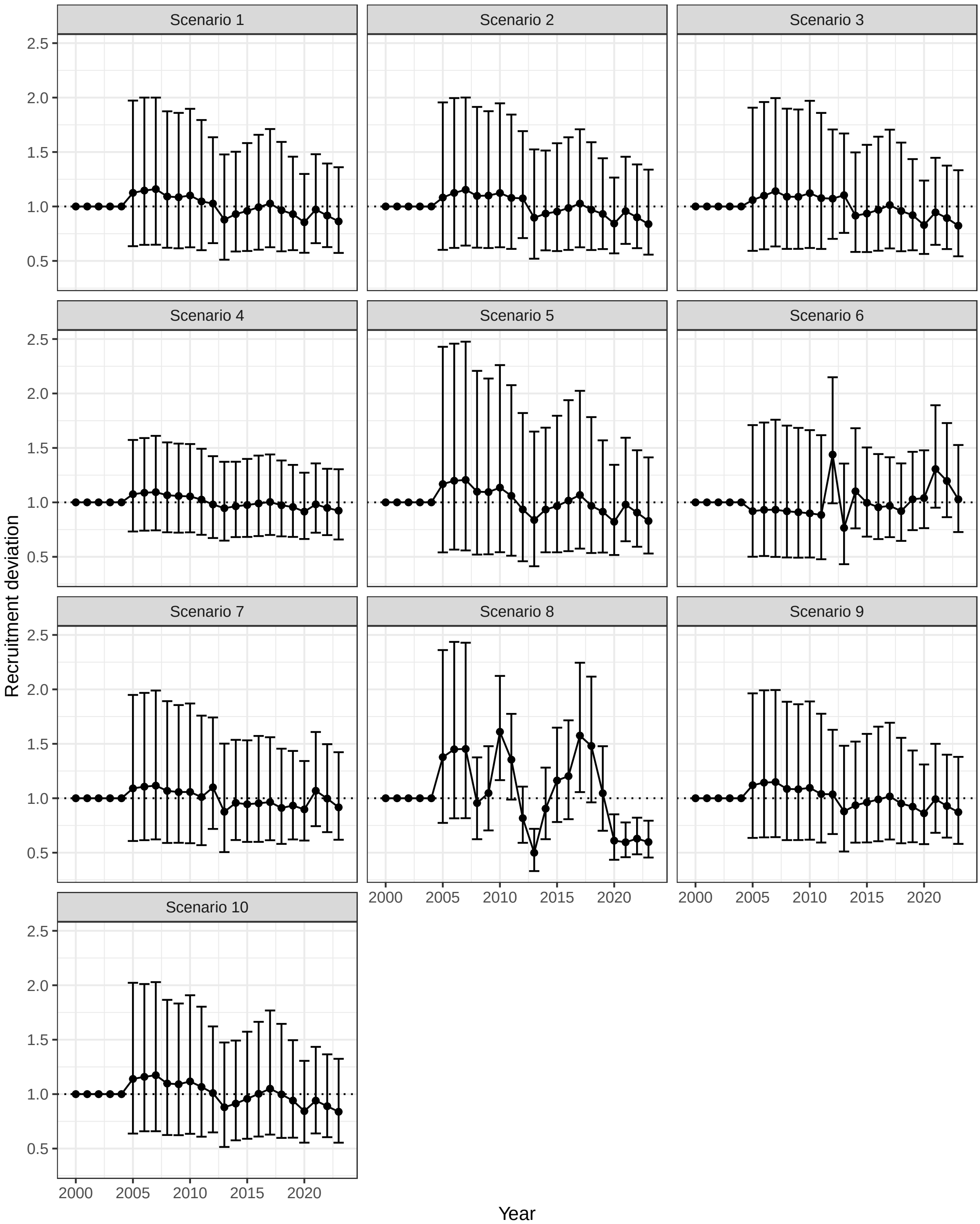


Figure H.13: Recruitment deviations for all sensitivity scenarios conducted for the Gould stock DDUST model, from 2000 to 2023.

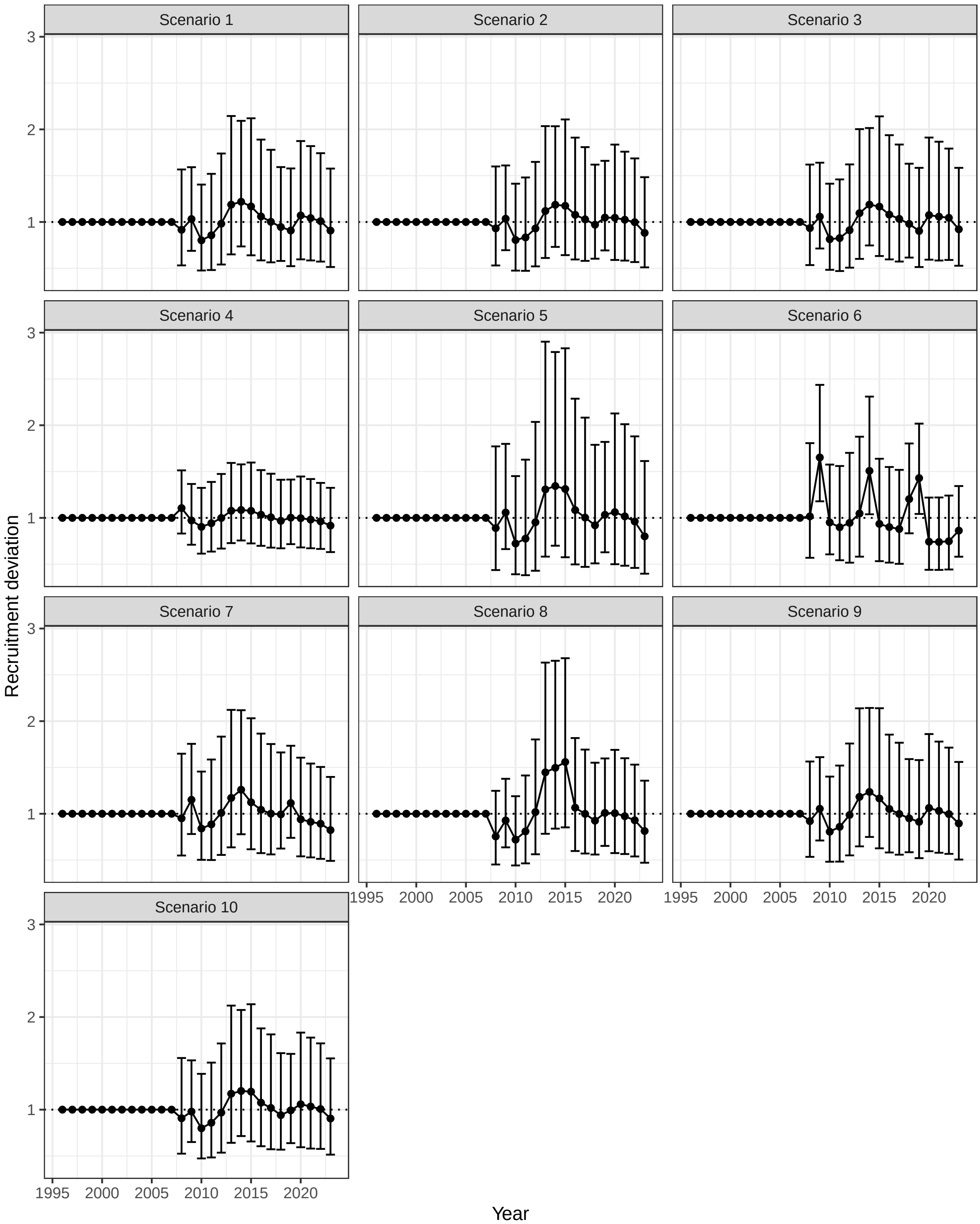


Figure H.14: Recruitment deviations for all sensitivity scenarios conducted for the Bunker stock DDUST model, from 1996 to 2023.

H.6 Fishing mortality

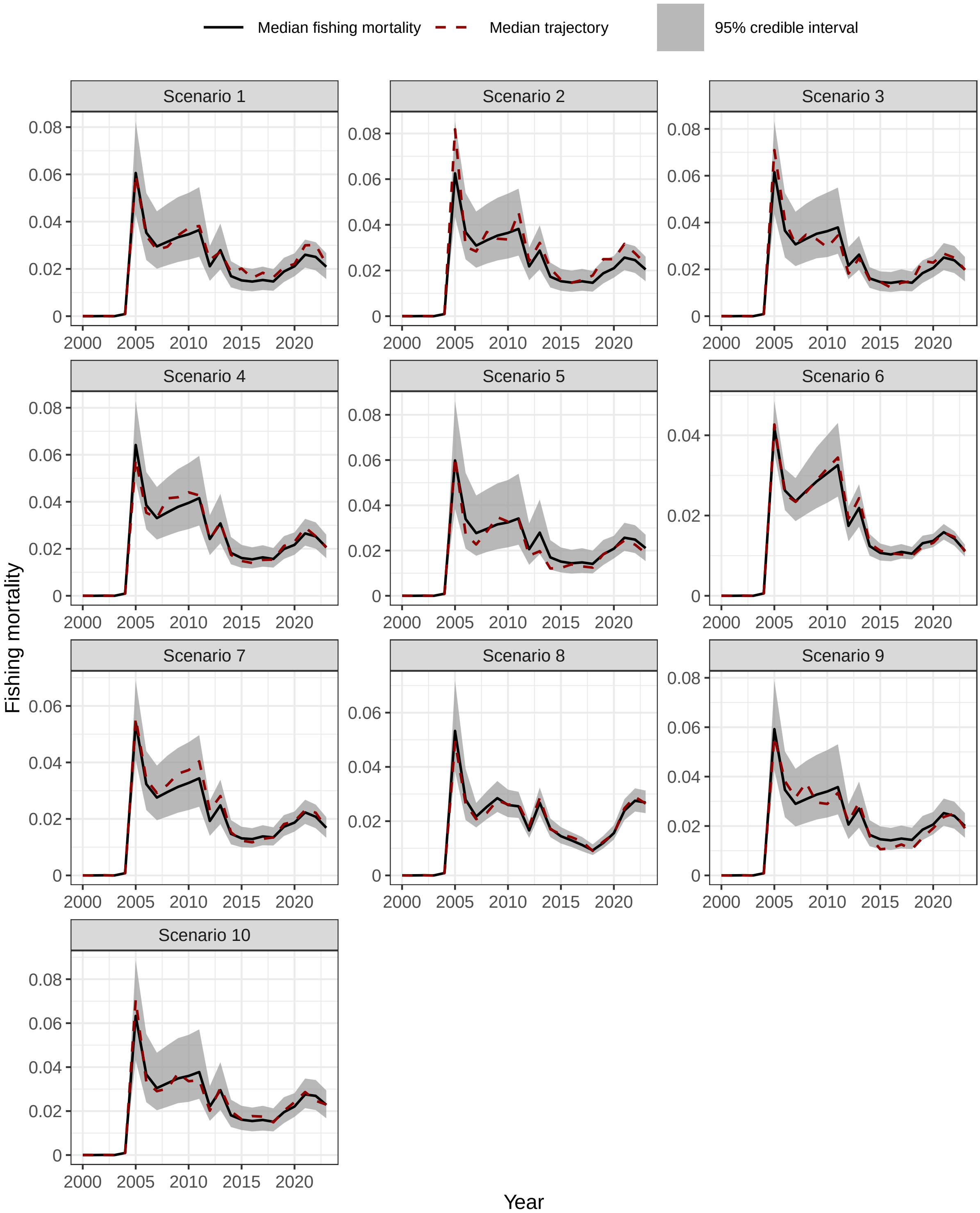


Figure H.15: Predicted fishing mortality (F) for all sensitivity scenarios conducted for the Gould stock DDUST model, from 2000 to 2023.

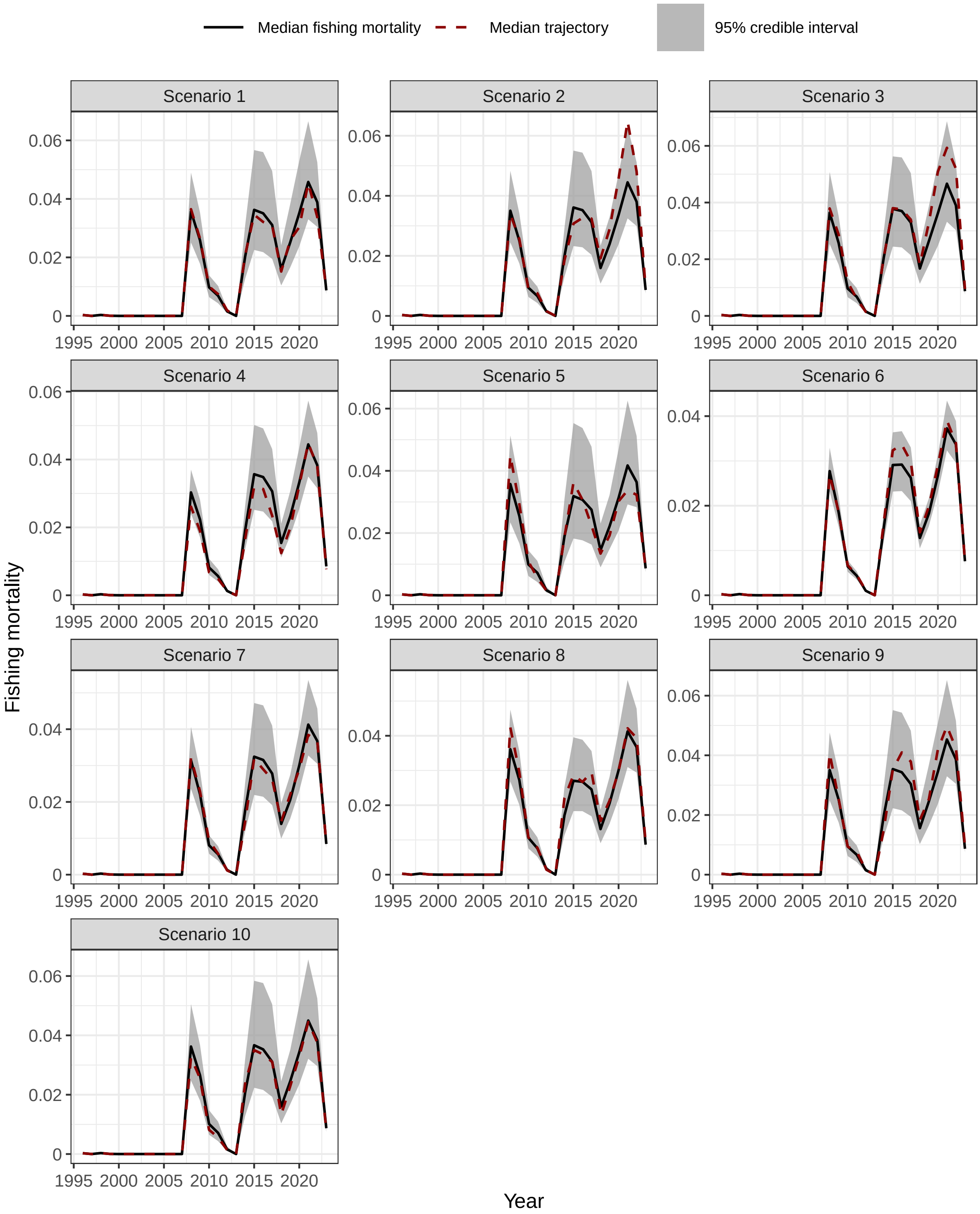


Figure H.16: Predicted fishing mortality (F) for all sensitivity scenarios conducted for the Bunker stock DDUST model, from 1996 to 2023.

Appendix I 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.

I.1 Mathematical formulation

I.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),

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

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

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 (I.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 (I.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.

I.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,

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

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 (I.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,

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

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,

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

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 (I.1) and (I.2) are updated using the recruitment deviations described in equation (I.4)

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

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

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

I.1.3 Spawning

The recruitment derived in equation (I.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

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

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,

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

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

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

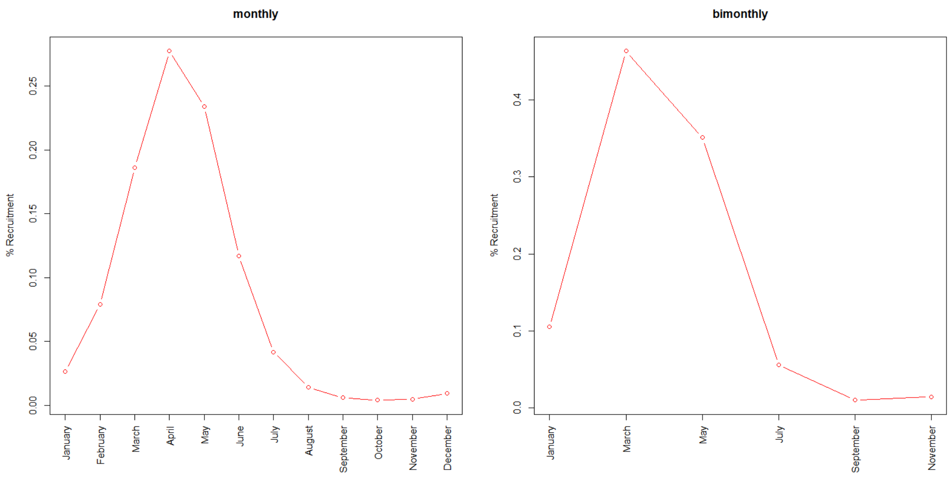


Figure I.1: Aggregation of a monthly recruitment pattern for a bi-monthly model

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

I.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

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

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 I.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.

I.1.5 Growth

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

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

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

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

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

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

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

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

Asymptotic weight from equation (I.16) is then

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

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:

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

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

I.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

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

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

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

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

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

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

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

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

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

Equilibrium spawning biomass is calculated as

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

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 I.3 are then

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

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

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).

I.2 Statistical framework

I.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,

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

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,

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

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,

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

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

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

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

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

The predicted abundance index is therefore

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

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

I.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,

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

I.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

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

The vulnerable biomass estimate log-likelihood is

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

The recruitment deviation log-likelihood in REDDUST is

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

The recruitment deviation log-likelihood in DDUST is

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

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

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

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 I.2a the prior on the transformed parameter ξ is

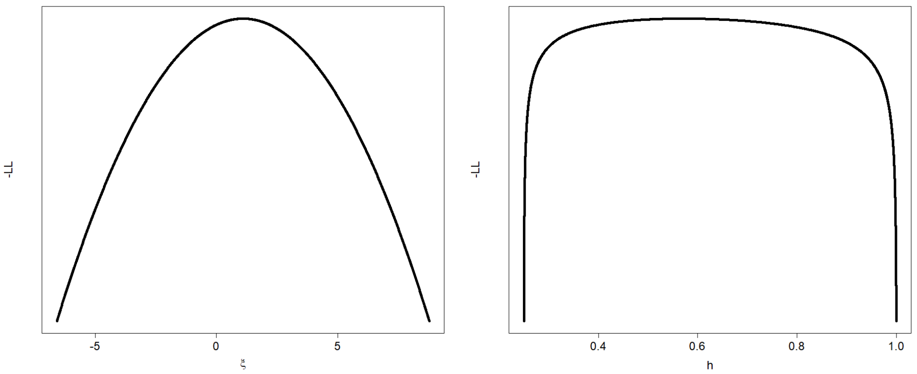
$$\xi \sim \text{Log-normal}(\mu_\xi = \log(3), \sigma_\xi^2 = 1). \tag{I.41}$$

Figure I.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

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

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

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



(a) log-normal prior of transformed parameter ξ

(b) transformed prior of original parameter h

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

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

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