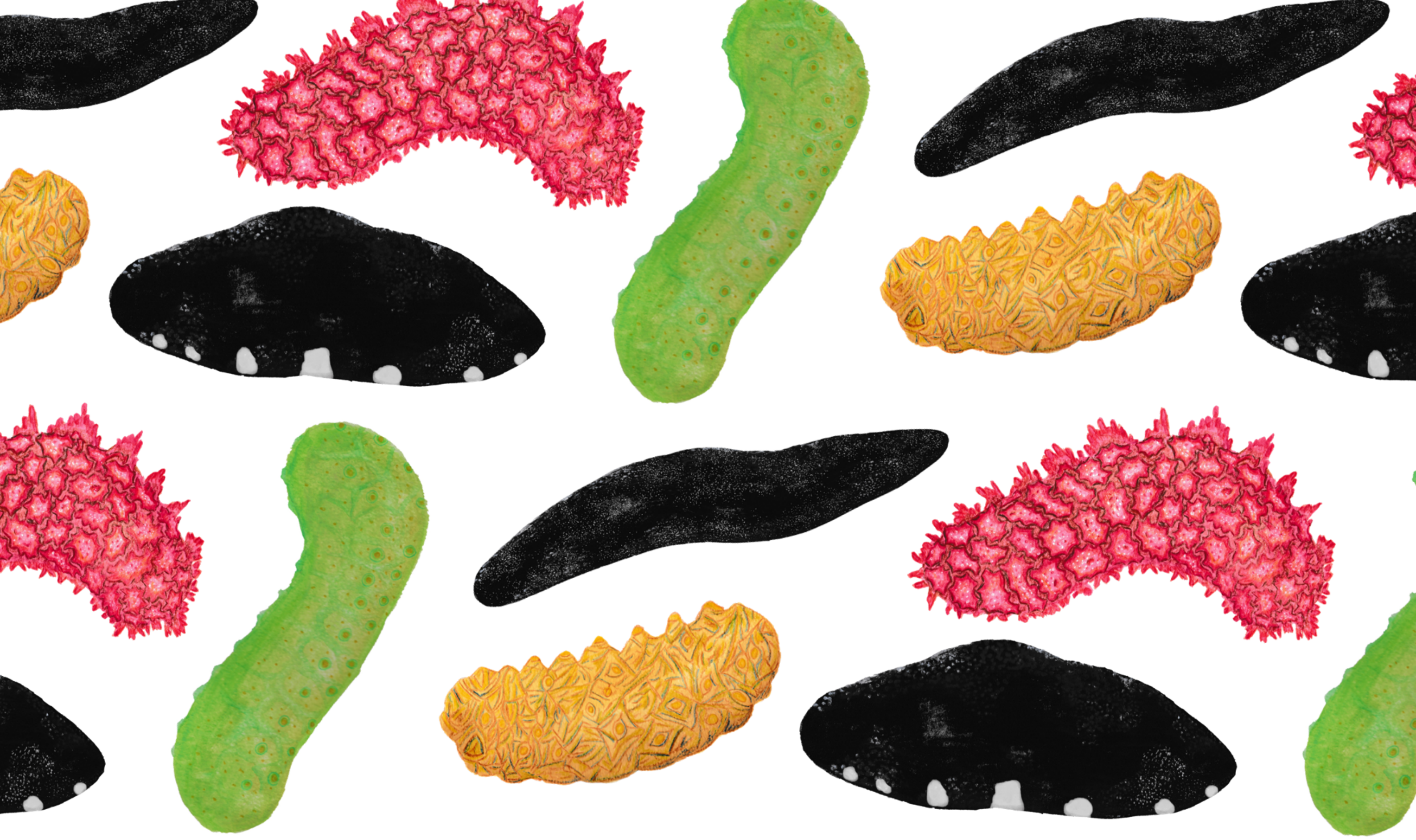

Management strategy evaluation of the Queensland east coast sea cucumber fishery, with data to June 2023

May 2024

Queensland Government

This publication has been compiled by M.E. Wickens, J.J. Smart, and J. Wortmann of Fisheries Queensland, Department of Agriculture and Fisheries.

Painting on cover page by Alise Fox.

Enquiries and feedback regarding this document can be made as follows:

Email:	info@daf.qld.gov.au
Telephone:	13 25 23 (Queensland callers only)
	(07) 3404 6999 (outside Queensland)
	Monday, Tuesday, Wednesday and Friday: 8 am to 5 pm, Thursday: 9 am to 5 pm
Post:	Department of Agriculture and Fisheries GPO Box 46 BRISBANE QLD 4001 AUSTRALIA
Website:	daf.qld.gov.au

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Summary

The Queensland Sea Cucumber Fishery is a predominantly commercial fishery located on the east coast of Queensland, Australia. The fishery has a dynamic history of species catch composition whereby the main target species were black teatfish *Holothuria whitmaei*, then white teatfish *Holothuria fuscogilva* and presently burrowing blackfish *Actinopyga spinea* with opportunistic harvest of herrmanni curryfish *Stichopus herrmanni* and prickly redfish *Thelenota ananas*.

Management strategy evaluation is a simulation tool for comparing the effectiveness of different management procedures against fishery objectives. The simulations capture the growth, reproduction, movement and mortality of a fish population and potential management procedures which dictate the fishery operating on the population. Uncertainty in these processes is characterised by running many simulations with slightly different biological specifications. The management procedures prescribe a mode of operation rather than a specific catch-limit or effort control. The performance of each management procedure is quantified to answer important management questions. Management procedures that perform well over a range of simulations are more likely to achieve the desired management goals. Well-performing management procedures become recommendations for the fishery.

The management strategy evaluation found the settings contained in the 'Queensland Sea cucumber fishery harvest strategy 2021-2026' and other legislated and enforceable management arrangements are likely sufficient to meet the fishery's objective of attaining maximum economic yield (defined in the harvest strategy as target biomass level of 60% of unfished biomass for stocks harvested in the fishery). The current management containing the rotational harvest strategy, catch limits and size limits suggests the risk of depletion for most species was low. Results indicated some risk to species with a history of high catch such as black teatfish, white teatfish and sandfish *Holothuria scabra* if similar catches were reinstated.

The rotational harvest strategy performed similarly to, and in most cases exceeded the performance of, the corresponding non-rotational management procedures with catch or size limits. In the high catch projections, the rotational harvest strategy did not necessarily improve the relative biomass, suggesting the rotational harvest strategy needs to be complemented with reasonable catch limits.

Evaluation of total allowable catch and catch trigger rules suggests a low risk to future overfishing when the total allowable catch is set to reflect the catch from the past ten years for all species. The species most likely, in relative terms, to experience stock decline under current catch limits are black teatfish and white teatfish due to their higher levels of exploitation placing the simulated biomass in 2023 at approximately 60% of unfished biomass. For both teatfish species, there was less than 1% probability that the biomass would fall below 20% of unfished biomass across all projection years, indicating current catch levels would maintain current stock levels, rather than produce stock declines.

Across management procedures, a minimum legal size 25% above the length-at-maturity provided substantial resilience to fishing as more individuals were able to reproduce prior to harvest. Minimum legal size management performed the best when paired with a total allowable catch and rotational harvest strategy.

A management strategy evaluation of the Queensland sea cucumber fishery conducted by CSIRO in 2014 evaluated the benefits of the rotational harvest strategy (Skewes et al. 2014). While some specific results differ between the previous and current management strategy evaluation and are difficult to compare as fishery reference points have been updated between reports, consistent conclusions were reached.

The three main data sources were logbook data for catch and effort trends, biological parameters provided by Fishwell Consulting and Macquarie University and co-produced stock assessment results. The stock assessments for burrowing blackfish, prickly redfish, herrmanni curryfish and vastus curryfish provided this management strategy evaluation with Stock Synthesis models which formed the operating model for the four species. The stock assessments were highly reliant on biomass estimates from surveys completed by Fishwell Consulting and their use as a foundation of the operating models therefore incorporates these biomass estimates into the management strategy evaluation.

The biology of many sea cucumber species is unknown or uncertain and often places this taxon in a data-limited space. This applies to many species in the Queensland sea cucumber fishery and the data-limited nature of the fishery has been captured in this management strategy evaluation through an increased level of uncertainty for species biology. A consequence of this is that more uncertainty occurs within the management strategy evaluation although this has not impacted the results which are able to confidently provide recommendations despite species knowledge gaps.

This management strategy evaluation was undertaken using the *openMSE* package developed by Blue Matter Science.

Acknowledgements

We would like to thank industry members who engaged in this project and provided feedback on important fishery dynamics: Chauncey Hammond (Seafresh Australia), Anton Krsinich (Tasmanian Seafoods), Ben Cochrane and Rhys Bennett. We would like to thank Matt Koopman and Ian Knuckey from Fishwell consulting who conducted the biomass surveys and provided constructive scientific critiques and discussions throughout the project. Dr Vincent Raoult and Professor Jane Williamson also provided valuable advice on species biology. We are grateful to Adrian Hordyk, Quang Huynh and Tom Carruthers for developing the *openMSE* R package and for providing advice on implementing the rotational harvest strategy within this framework. We also thank the following Fisheries Queensland scientists and staff for their support, input and advice to this assessment: Dr Alex Campbell, Dr Michael O'Neill, Sue Helmke, Jenny Keys, Michelle Winning, Dr Peter Kind and Jennifer Larkin. We also thank the broader Fisheries Queensland stock assessment team for their insight and feedback on the assessment models during the 2023 team workshop. We thank Alise Fox for providing the cover art.

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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
FQ	Fisheries Queensland
GBR	Great Barrier Reef
GBRMP	Great Barrier Reef Marine Park
h	Steepness parameter of the Beverton-Holt stock recruitment relationship
harvest	component of the catch that is kept by fishers, also referred to as ‘retained catch’ and ‘landed catch’
historical period	The simulated fishery from the OM for the years where catch data are available
legal size biomass	The total weight of fish in a population susceptible to fishing, the primary biomass measure reported by DDUST
OM	Operating model. Used to simulate the population and fishing fleet dynamics within the MSE
M	Natural Mortality
MLS	Minimum legal size
MSE	Management strategy evaluation
MSY	Maximum sustainable yield defined as dead catch
MP	Management procedure. A management mechanism applied within MSE simulations
PM	Performance metric which is used to assess the success of an MP. Usually presented as the % of simulations that stayed within a reference point
projection period	The simulated fishery from the OM beyond the years where catch data are available
t	tonnes
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’
RHS	Rotational harvest strategy. Also referred to as rotational harvest arrangement (RHA) in other documents
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
TAC	Total allowable catch
WTO	Wildlife Trade Organisation

1 Introduction

Management strategy evaluation (MSE) is a simulation tool for comparing the effectiveness of different management procedures (MPs) against fishery objectives. The simulation captures the growth, reproduction, movement and mortality of a fish population and potential MPs which dictate the fishery operating on the population. It is important to understand that MPs prescribe a mode of operation such as the 'hockey stick' rule rather than a specific catch-limit or effort control (Hordyk et al. 2017; Punt et al. 2016). Uncertainty in these processes is characterised by running many simulations with slightly different biological specifications. The performance of each MP is quantified to answer questions such as 'what percentage of simulations maintain a biomass above 60%?' or 'what is the probability that yield will decrease?'. MPs that perform well over a range of simulations are more likely to achieve the desired management goals. Well-performing MPs become recommendations for the fishery.

A common misconception of MSE is that the current population status will be estimated. This role is reserved for stock assessments which aim to accurately construct historical changes in biomass and determine the current biomass depletion of a stock. MSE, on the other hand, is less concerned with current stock status and more concerned with potential future projections of the fishery (Hordyk et al. 2017). MSE may use similar data to replicate historical growth, reproduction, movement and mortality and may be informed by previous stock assessment work. But ultimately, an MSE will test a wider range of potential depletion levels than a stock assessment has estimated in order to evaluate the performance of an MP in unforeseen circumstances.

The Queensland Sea Cucumber Fishery (QSCF)—formerly the east coast beche-de-mer fishery—is a commercial and recreational fishery located on the Queensland east coast, beyond the GBRMP, and over the Suamarez and Marion reefs between latitudes 11° S and 26° S. The fishery is comprised of 21 species categorised into tier 1 and tier 2 species. Black teatfish *Holothuria whitemaei*, white teatfish *H. fuscogilva*, and burrowing blackfish *Actinopyga spinea* are tier 1 species. Amberfish *Thelenota anax*, blackfish *A. palauensis*, black lollyfish *H. atra*, brown sandfish *Bohadschia vitiensis*, deep water redfish *A. echinites*, elephant trunkfish *H. fuscopunctata*, flowerfish *H. arenicola*, golden sandfish *H. lessoni*, greenfish *Stichopus chloronotus*, herrmanni curryfish *S. herrmanni*, leopardfish *B. argus*, pinkfish *H. edulis*, prickly redfish *T. ananas*, sandfish *H. scabra*, snakefish *H. coluber*, stonefish *H. lecanora*, surf redfish *A. mauritiana*, and vastus curryfish *S. vastus* are tier 2 species. The fishery is managed according to the 'Queensland sea cucumber fishery harvest strategy: 2021–2026' (Fisheries Queensland 2021).

Beche-de-mer have a long cultural history in Queensland as a traditional food source for Aboriginal peoples and Torres Strait Islander peoples. Upon colonisation, the labour of skilled Aboriginal peoples and Torres Strait Islander peoples was exploited to commercialise the fishery. One of the first protection acts, the *Pearl Shell and Beche-de-mer Fishery Act of 1881*, was legislated to regulate the working conditions in the fishery. Over the next sixty years, the fishery continued to grow and many legislations were enacted to prevent the unfair treatment of Aboriginal peoples and Torres Strait Islander peoples. The end of World War II saw a cessation of sea cucumber catch which may have been driven by overfishing of shallow, inshore species or political or economic reasons (Uthicke 1993).

The fishery recommenced in the 1990s with the main target species of black teatfish with opportunistic harvest of sandfish and prickly redfish. In the late 1990s, operators of this fishery explored the market for new species, many of which were harvested in small quantities for a short amount of time as the demand was not found. The fishery shifted to white teatfish following fishery closures to the black teatfish and sandfish fisheries due to stock declines. From 2003 onwards, the fishery was dominated by burrowing blackfish with smaller, approximately equal contributions from white teatfish, prickly redfish and herrmanni curryfish.

The key management tool used in the QSCF is the rotational harvest strategy (RHS) which divides the fishery into 158 areas and opens each area every three years. The RHS aims to spread effort across the fishery to prevent localised depletion. Input and output controls also limit vessel numbers, the number of days spent in each area and the tonnage removed. The historical and current management of the fishery is outlined in Section 1.1 and Table 1.1.

A previous MSE of the QSCF in 2014 evaluated the benefits of the RHS (Skewes et al. 2014). Skewes et al. (2014) found that the RHS reduced the risk of localised depletion overall but some risk remained for highly targeted species. The results from Skewes et al. (2014) aided the development of catch trigger limits (Fisheries Queensland 2021).

Sea cucumber fisheries have a tendency of over-exploitation likely arising from fishery development outpacing science (González-Wangüemert et al. 2018; Friedman et al. 2011). It is common in sea cucumber fisheries that one or two species are targeted and when the densities become low, the fishery shifts effort to another species with economic promise, creating a pattern of serial depletion (Anderson et al. 2011). Many sea cucumber fisheries have had a 'boom and bust' life cycle which has unfortunately been predictable for some emerging tropical fisheries (Anderson et al. 2011). A known issue with sea cucumbers is their slow rate of recovery following population depletion, which has been attributed to recruitment depensation through the Allee effect (Friedman et al. 2011; Bell et al. 2008). There is evidence of this for some Queensland species as Uthicke et al. (2004) and Koopman et al. (2024b) observed no recovery of sea cucumber populations after an extended absence of fishing. Of particular relevance, Uthicke et al. (2004) found black teatfish production to be very low and suspected that recovery of black teatfish stocks on the GBR may take several decades. Therefore, MSE for sea cucumber fisheries are particularly important as proactive fisheries management that minimises the risk of the overfishing is the best approach to avoiding depleted populations that are slow to recover.

There are critical gaps in biological knowledge preventing the perceived success of management strategies in the QSCF (Eriksson et al. 2015; Wolfe et al. 2022). This has occurred as most of the fishery's management has evolved through a proactive common sense approach developed by industry. However, this evolution has not been underpinned by a suitable level of science. The lack of scientific research underpinning the RHS has been a repeated criticism of the fishery (Eriksson et al. 2015; Purcell et al. 2015; Wolfe et al. 2022). However, large strides have been made in recent years through biomass surveys for multiple species (Knuckey et al. 2016; Koopman et al. 2019; Knuckey et al. 2021; Koopman et al. 2022; Koopman et al. 2023; Koopman et al. 2024a) and the first stock assessments for tier 1 and important tier 2 species (Helidoniotis 2021a; Helidoniotis 2021b; Smart et al. 2024a; Smart et al. 2024b).

The purpose of this report is to fulfill condition 5 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 5 of the WTO application states that:

"The Queensland Department of Agriculture and Fisheries must commission a Management Strategy Evaluation (MSE) to evaluate the ability of the settings contained in the 'Queensland sea cucumber fishery harvest strategy 2021-2026' and any other legislated and enforceable management arrangements to meet the fishery's objectives of attaining maximum economic yield (defined in the harvest strategy as target biomass level of 60% of unfished biomass for stocks harvested in the fishery). The MSE must consider the risk posed to each individual species harvested in the fishery, identify information needs and make recommendations for any improvements to the management arrangements considered necessary for the management of the fishery to meet its objective.

a) The scope and Terms of Reference for this review should be developed in consultation with the Department of Climate Change, Energy, the Environment and Water.

b) The updated MSE must include all new data, including data from fishery independent surveys. The updated MSE must be published on the Queensland Department of Agriculture and Fisheries website by 30 May 2024.

c) The outcomes of the MSE must be considered as part of an implementation plan to be provided to the Department of Climate Change, Energy, the Environment and Water by 30 May 2024. The implementation plan must outline how and when any required changes to the management of the fishery will be delivered."

1.1 Management

The QSCF is managed under the Fisheries Act 1994 and the Queensland sea cucumber fishery harvest strategy 2021–2026 (Fisheries Queensland 2021). The fishery's operation is also guided by ad-hoc management decisions made by the two operators of the fishery. This has resulted in a mixed management approach unique to this fishery that is responsive but largely untested.

Table 1.1: History of Queensland sea cucumber fishery management

Year	Management change
pre 1800's	Development of large-scale commercial beche-de-mer fisheries.
1881–1939	The Queensland legislature enacted the *Pearl Shell and Beche-de-mer Fishery Act of 1881*. Commercial harvest continued until the end of World War II.
1980's	Fishing resumed, mostly targeting black teatfish. Almost 30 licence holders.
1988	Compulsory commercial catch logbook reporting commenced.
1991	Overall total allowable catch (TAC) was set at 500 tonnes (wet gutted weight). Additional quota was provided to applicants when they had harvested their total allocation within the quota year.
1995	From January, entry to the fishery was limited to fishers with history; no new licences to be handed out. Introduction of logbook version BD01 requiring both numbers and weight of sea cucumbers to be reported.
1998	Overall TAC reduced to 380 tonnes (wet gutted weight).
1999	Closure of black teatfish in October. Effort switched to white teatfish and a TAC was set at 127 tonnes for White teatfish.

Table 1.1 – *Continued on next page*

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Year	Management change
2000	Logbook version BD02 improved species differentiation among 'other species'. White teatfish TAC increased by 25% to 158 tonnes to compensate fishers in part for costs associated with Vessel Monitoring Systems (VMS).
2001	Fishing for sandish in Hervey Bay and Tin Can Bay closed until evidence of stock recovery. White teatfish TAC returned to 127 tonnes.
2003	Effort switched to burrowing blackfish. Introduction of white teatfish zones: Zone 1 is north of 19° S and Zone 2 is south of 19° S. White teatfish TAC reduced to 89 tonnes (56.8 tonnes in Zone 1 and 32 tonnes in Zone 2).
2004	Formulation and implementation of the Rotational Zoning Plan (now Rotational Harvest Strategy). White teatfish TAC returned to 127 tonnes (57 tonnes in Zone 1 and 70 tonnes in Zone 2). Three authority holders operating in the fishery. Representative Areas Program (RAP) introduced, comprehensive rezoning of the whole Great Barrier Reef protecting a total of 37% of the fishable habitat in the GBRMP from sea cucumber fishing.
2005	White teatfish TAC reduced to 89 tonnes.
2006	TAC reduced to 361 tonnes (salted or par boiled and frozen). Logbook version BD03 requires only the number of sea cucumbers and the weight is recorded on buyer return logbook.
2007	TAC weights adjusted to reflect processed (salted or blanched) weights. White teatfish TAC reduced to 70 tonnes (57 tonnes in Zone 1 and 13 tonnes in Zone 2).
2008	White teatfish TAC reduced to 53 tonnes (40 tonnes in Zone 1 and 13 tonnes in Zone 2). 18 symbols, 9 active licences held by three operators. Implemented the performance measurement system (PMS) that included species-specific review reference points based on annual catches of all targeted species that made up the 'other' quota group.
circa 2008	Species-specific minimum size limits (sandfish 20 cm; white teatfish 40 cm; black teatfish 30 cm; prickly redfish 50 cm; blackfish 20 cm; deep water redfish 20 cm; surf redfish 25 cm; lollyfish 20 cm; greenfish 20 cm; curryfish 35 cm; elephant trunkfish 40 cm; brown sandfish 25 cm; leopard fish 35 cm; amberfish 50 cm; all other species 15 cm).
2009	Compulsory reporting of rotational zone.
2010	White teatfish TAC increased to 64 tonnes (51 tonnes in Zone 1 and 13 tonnes in Zone 2).
2011	New conversion rate for quota means White teatfish TAC reduced to 53 tonnes.
2013	Logbook version BD04 requires reporting of weights and further improved species differentiation among 'other species'.
2014	Removal of White teatfish zones.
2019	White teatfish TAC reduced to 53 tonnes. Black teatfish reopened with TAC of 28.6 tonnes.

Table 1.1 – *Continued on next page*

Table 1.1 – *Continued from previous page*

Year	Management change
2020	Queensland sea cucumber fishery harvest strategy 2021–2026 implemented. Species-specific individual transferable quotas (ITQ) for black teatfish and white teatfish. Combined ITQ for Other Species (OS).
2021	Logbook version BD05 requires estimated weights and number of containers.
2022	Species specific reporting of curryfish required by condition 8(a) of the WTO export application.

The history of management of the modern commercial QSCF is outlined in Table 1.1. Current management adheres to the QSCF harvest strategy developed in 2021 to manage sea cucumber resources of Queensland (Fisheries Queensland 2021). The harvest strategy outlines that every species in the QSCF has a target exploitable biomass of 60% relative to unfished exploitable biomass as a proxy for biomass at maximum economic yield (B_{MEY}).

The decision rules for setting a sustainable harvest to achieve the target are based on a 'hockey stick' approach (see Figure 1.1). This is where the TAC is set based on a linear relationship between B_{20}, where the level of fishing mortality (F) is equal to zero, and B_{60} where F is set at the level to achieve B_{60}. The 'hockey stick' rule takes into account the current biomass level of the stock for determining the TAC to achieve the target biomass. The recommended TAC is calculated by applying the rate of fishing mortality to achieve B_{60} to the current biomass level. As a result, the recommended TAC represents the total catch that can be harvested in the following years, to move the current biomass level towards the target level.

Each species in the QSCF is also subject to an individual trigger reference level designed to set catch levels appropriate for achieving the 60% biomass target set for sea cucumber species (see Table 1.2). Trigger reference levels are catch triggers used to inform increases in fishing mortality. Annual catch levels are assessed against the trigger reference level to detect changes in catch that may represent an unacceptable risk to an individual quota group. If the annual catch for a species exceeds its trigger reference level, then a TAC will be set to maintain the annual catches of that species at, or below, the trigger reference level until a further assessment can be undertaken. Other performance indicators for the stock (e.g. stock status, length frequency distributions, standardised commercial catch rates, total harvest etc.) will also be reviewed by the sea cucumber fishery working group to ensure that stocks are performing in a way that will achieve the target biomass.

Species-specific TACs are in place for white teatfish (currently 53 tonnes) and black teatfish (currently 30 tonnes). If the annual harvest of burrowing black fish for the defined regions is more than the following catch levels – 120 tonnes at Lizard reef, 45 tonnes at Gould reef, 60 tonnes at Bunker reef – then a competitive TACC will be set at the trigger level and an assessment will be required to determine the risk of localised depletion. The remaining species are subject to a combined TAC of 308 tonnes. Trigger levels correspond to the main landed product form of each species. This is predominantly salted weight with the exception of burrowing blackfish which are landed in boiled and frozen weight. There are size-limits in the QSCF designed to correspond with length-at-maturity and allow individuals to breed once before being fished 1.1.

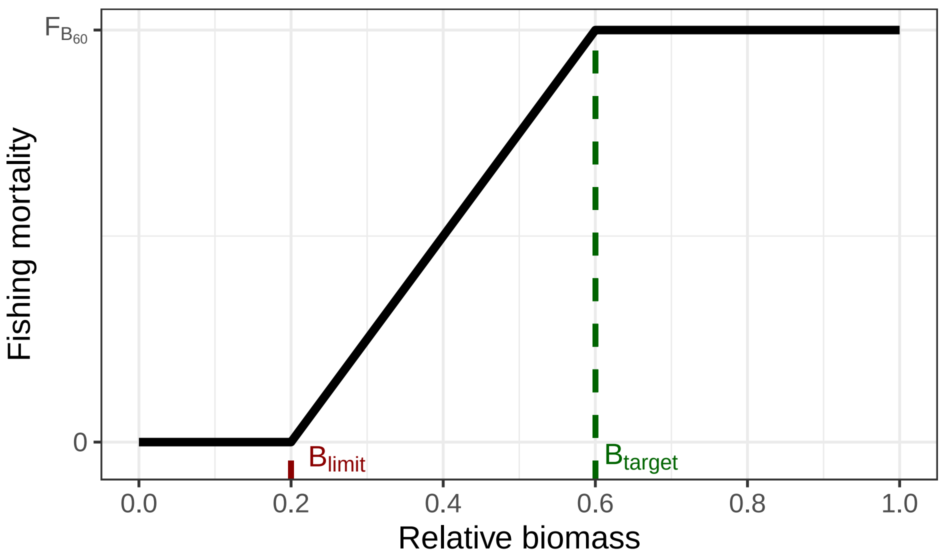

Figure 1.1: The hockey stick harvest control rule. Fishing mortality is zero when current biomass is at or below the relative biomass limit of 20%. Fishing mortality is set to achieve the biomass target level when the current biomass is at or above the relative biomass target of 60%. Fishing mortality is set based on a linear relationship between 0 and $F_{B_{60}}$ if current relative biomass is between the limit and target.

Table 1.2: Trigger reference levels for Tier 2 species. These trigger reference levels were developed in consultation with industry and Tim Skewes from CSIRO in 2004. They were deemed to be estimates of "safe" exploitation levels for the entire east coast fishery given the likely population size and the level of information known about a species.

Species	Trigger (t)	Reason
Amberfish	50	Widespread, very large species
Blackfish	25	Widespread, common species
Brown sandfish	25	Low abundance in TS but likely to be widespread and abundant on east coast
Herrmani curryfish	50	Widespread, large species
Vastus curryfish	25	Reasonably common
Deep water redfish	25	Locally high abundance in inshore areas
Elephant trunkfish	50	Widespread, abundant and large species
Flowerfish	25	Common reef edge species
Greenfish	50	Widespread, abundant species
Golden sandfish	10	Unknown density in Torres Strait but probably relatively low. May be increased abundance in southern GBR. Not much known about this species
Leopardfish (a.k.a. tigerfish)	25	Widespread, common species
Lollyfish	50	Very abundant, ubiquitous species
Pinkfish	50	Widespread, very abundant species
Prickly redfish	40	Currently targeted, widespread distribution, large species
Sandfish	15	Prone to overexploitation, restricted distribution and isolated populations
Stonefish	10	Not much known about this species, potentially restricted distribution
Snakefish	25	Widespread species
Surf redfish	25	Targeted species, reasonably widespread, good recovery rates

Other restrictions include:

- A licence is restricted to one primary boat and up to four tenders no longer than 7 meters in length and 10 divers.
- Tenders must not exceed 5 nautical miles from the primary boat.
- Only hookah and SCUBA are permitted gear in the commercial fishery.
- No breathing apparatus is permitted in the recreational sector.
- Recreational harvest is restricted by an in-possession limit of 5 sea cucumbers per person and a total boat limit of 10 sea cucumbers.
- Recreational harvest is prohibited south of Bowen.

The QSCF also operates under a rotational harvest strategy (RHS), that splits the fishery into 158 zones (see Figure 1.2) in an effort to reduce the risk of localised depletion. Each zone is available every three years for a maximum of 18 days of fishing. This was previously a 15 day limit which allowed a fishing day to be paused and later resumed should inclement weather occur. However, with a change to a strict calendar day limit, this number was increased. This change reduced pressure on industry to continue fishing in poor or dangerous weather once they started a fishing day, and provided a similar level of overall effort to the previous 15 day limit that allowed cumulative partial days.

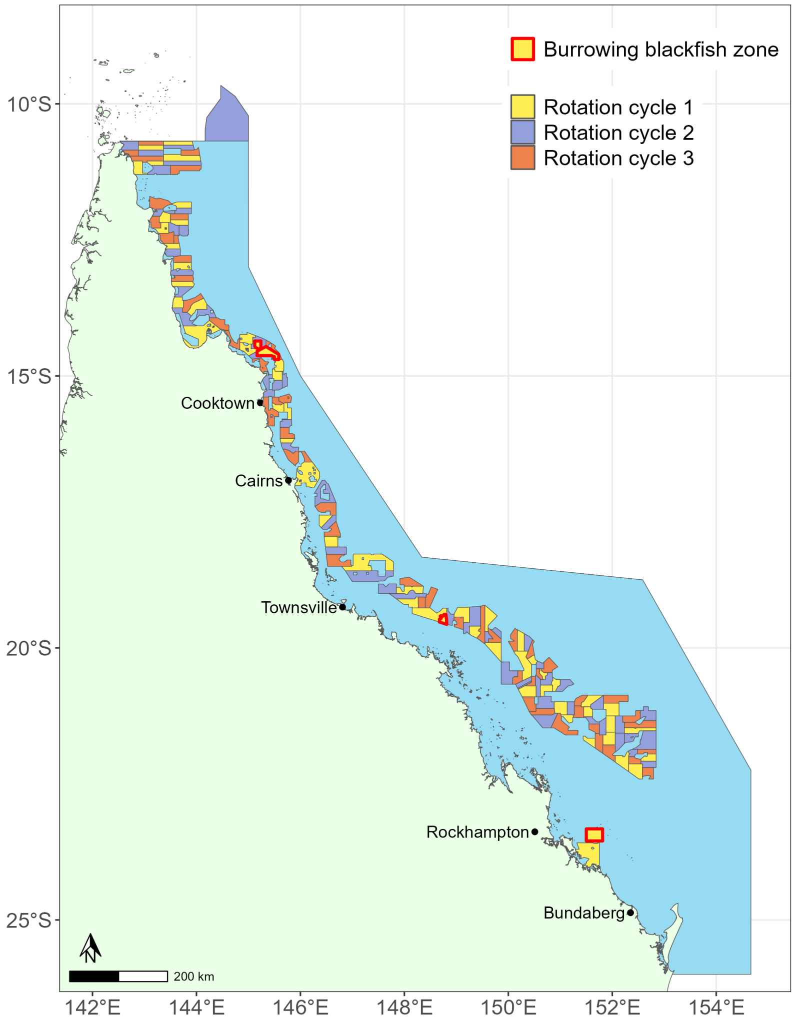

Figure 1.2: Rotational harvest zones within the B1 Fishery of QSCF. Zones are made available every three years for a maximum of 18 days allowed per zone. Zones in rotation cycle 1, 2 and 3 were first available in 2004, 2005 and 2006 respectively.

Burrowing blackfish are exempt from the RHS as they are predominantly located in three reefs: Lizard, Gould and Bunker (see Figure 1.3) which may be fished every year. Lizard reef and Waining reef are the northernmost zone, located north of Cooktown. The two reefs form one zone referred to collectively as 'Lizard'. Gould reef is the smallest burrowing blackfish zone (BBZ) and is located north of Airlie Beach. Bunker reef is the largest and southernmost zone and is located east of Rockhampton.

Tier 2 species are available for fishing in the BBZ in line with rotation cycle 1. Burrowing blackfish are also found across the GBR in much lower densities and can be harvested from the 158 zones in accordance with the RHS.

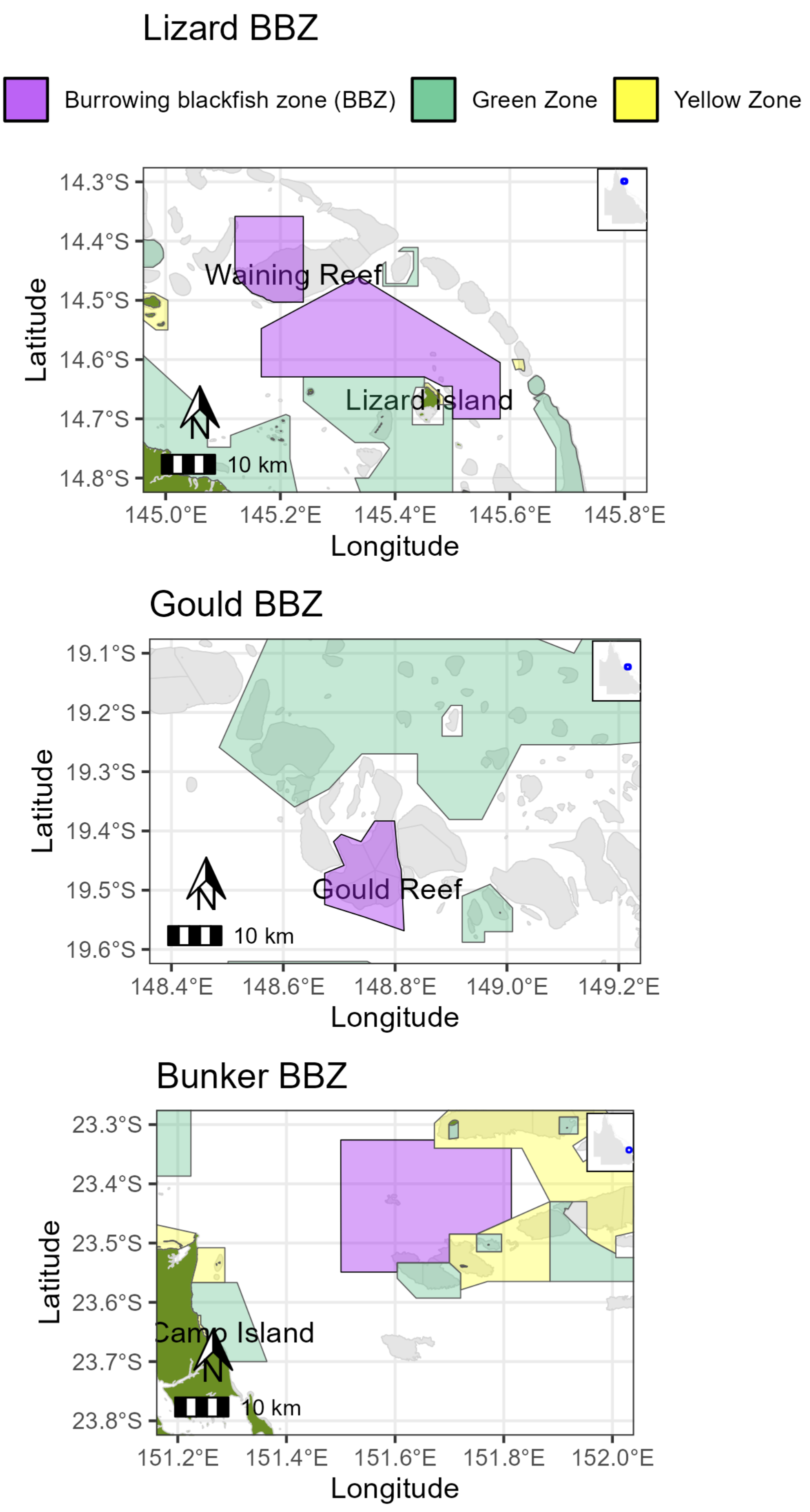

Figure 1.3: Map of the three Queensland sea cucumber fishery burrowing blackfish zones and their location along the Queensland coast. Green zones and yellow zones are closed to fishing.

2 Methods

2.1 Application of the *openMSE* framework

This MSE was undertaken using the *openMSE* package developed by Blue Matter Science (Hordyk et al. 2023b). *openMSE* is an umbrella package encompassing *DLMtool* (Carruthers et al. 2023), *MSEtool* (Hordyk et al. 2023a) and *SAMtool* (Huynh et al. 2023), each of which handle a different but complementary aspect of the MSE process. It is a flexible framework providing users with a variety of MSE options and features that can be easily experimented with and assessed. It allows the user to build an operating model, apply a variety of MPs, and easily compare and assess their performance. One of the main benefits of *openMSE* is that it does not require the user to program the MSE, saving substantial time and resources. Removing the programming requirements therefore frees up resources so that users can focus on implementing and evaluating the MSE, rather than spending the majority of their energy on model construction. However, *openMSE* remains fully customisable, allowing users to design and build their own MPs and performance metrics (PMs). *openMSE* also allows a range of data sources to be considered and provides guidance on how to consider a range of data-limited to data-rich fishery scenarios. A website maintained by Blue Matter Science provides a comprehensive guide to the *openMSE* package (`https://openmse.com/`).

The operating model within *openMSE* is an age-structured spatial population model that can simulate a wide variety of fishery dynamics. The package has been used for a variety of fisheries covering a broad range of taxa. However, one of the first fisheries assessed using the framework was the warty sea cucumber fishery (*Apostichopus parvimensis*) in California (Hordyk et al. 2017) which provides substantial guidance for the application of *openMSE* to the QSCF. The MSE presented here includes substantial customisation to capture the complex dynamics of the QSCF, including the tuning of operating models to match fleet dynamics, creation of spatial MPs to describe GBRMP zoning and the fishery RHS and bespoke PMs to assess the results against the fishery's harvest strategy (Fisheries Queensland 2021).

The *openMSE* framework contains a series of interactive components that comprise the MSE process. Figure 2.1 shows how the various components of the MSE link together. Yellow blocks indicate *openMSE* objects, green blocks indicate *openMSE* functions that operate on *openMSE* objects, blue blocks indicate features of the *openMSE* framework.

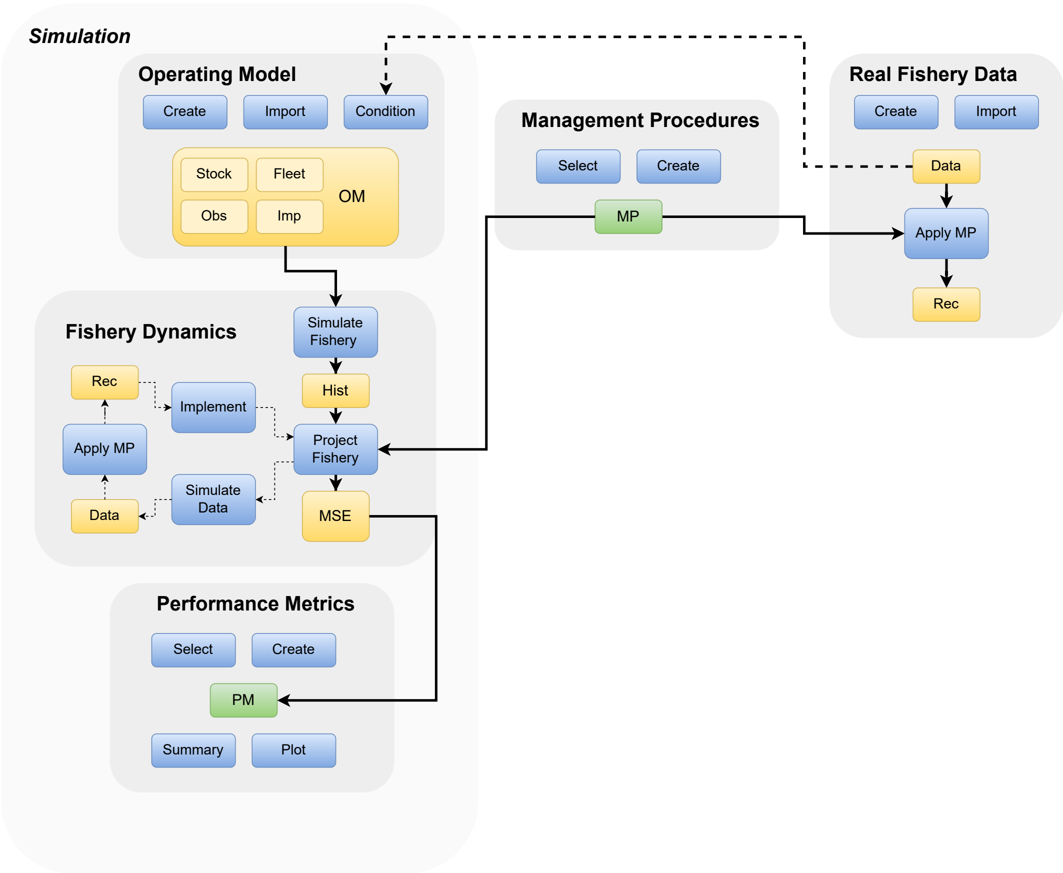

Figure 2.1: Diagram of *openMSE* components from https://openmse.com/welcome-map/. Yellow blocks indicate *openMSE* objects, green blocks indicate *openMSE* functions that operate on *openMSE* objects, blue blocks indicate features of the *openMSE* framework.

The main yellow block is the operating model (OM) object containing the settings for simulation of the stock, fleet, data observations and implementation of management. With sufficient data, the operating models may be conditioned on real fishery data (see the dashed line) or imported from a stock assessment. The OMs contain biological information on growth, maturity, stock size as well as fishery information such as selectivity, effort, observation error and implementation error. Any uncertainty in parameters can be provided to the OM as a uniform distribution or a vector of parameter values for each simulation. Each simulation draws a new parameter combination.

There are two green blocks representing the types of functions that operate within the MSE. A management procedure (MP) is applied to the fishery simulation and defines an input or output control rule for the fishery. Most MPs are dependent on observed data. The other function is a performance metric (PM) which quantifies the performance of an MP according to fishery objectives.

The simulation of the fishery dynamics is a two-step process. First, the OM settings guide the historical simulation representing the fishery from the inception year to the current year. Second, each MP is applied to project the fishery into the future. Each year that the MP is applied, simulated data is extracted from the simulated fishery, the data is analysed as per the MP and the resulting recommendation is implemented. This cycle is repeated for every assessment year of the projection period. The result is a time series of the population dynamics from the beginning of the historical period to the end of the projection period that has been subjected to the fishery rules outlined in the management procedure. The projected fishery is then appraised by the PM functions.

The process is repeated for many simulations which results in a variety of plausible fishery characterisations so the MPs are evaluated over a range of plausible situations. Importantly, the same historical spool-up is provided to each MP so performance can be confidently attributed to the management procedure, not randomness in the OM. Ideally, the recommended MPs perform well across all the simulations.

2.2 Data sources

Various data sources guided the design and governing quantities of the operating models. Sections 2.2.1 – 2.2.4 describes the source and use of each data type.

2.2.1 Spatial scope

The QSCF area consists of the area of all tidal water east of longitude 142°31'49" E between latitude 10°41' S and latitude 26° S (Thursday Island to Double Island Point) and the Ashmore and Boot Reefs area (see Figure 1.2).

The species evaluated in this MSE are protected by green zones and yellow zones introduced in July 2004 through the GBRMP Representative Areas Program (RAP). These zones cover 37% of the GBR and have been included in the population models to incorporate the populations within them that contribute to GBR-wide recruitment. Therefore, the OMs represent the biomass that is vulnerable to fishing by the commercial sector as well as the biomass protected by RAP.

An exception to this, is that the population models for burrowing blackfish are restricted to the BBZ and the surrounding green zones. The burrowing blackfish biomass that exists outside of the BBZ in fished areas are not represented in this MSE.

2.2.2 Harvest estimates

QSCF logbook data were introduced in 1988 and, through many iterations, required either the numbers or weight of harvested animals to be reported. Buyer records were introduced in 2000-2001 and mandated the reporting of weight. Therefore, buyer records were a more reliable data source and used for the period of 2000-2001 to present. The logbook data prior to 2000-2001 was adjusted according to the scaled weight discrepancy in the buyer records period.

Additionally, the logbook data and buyer records represent the landed weight or catch in number depending on the individual logbook or buyer return rather than the whole, unprocessed weight. Where number of sea cucumbers is recorded rather than catch in weight, landed weights are calculated from the mean individual weights of each species for their various product forms. This was determined from records that report numbers and landed weights for each species and product form. Buyer data is used over logbook data where available due to increase accuracy of reported landed weights. Individual logbook catches (i.e., catch records, not aggregated annual catches) are scaled to match buyer data returns. Buyer data records contain multiple trips and therefore have to be aggregated. A scalar for each year is calculated between buyer and logbook records and applied to each species. The scaled logbook catches were used in the CPUE analyses, rather than raw catch records. Landed weights were converted to whole weights using conversion factors from the Torres Strait Fishery (Murphy et al. 2021). The logbook processing methods presented here correspond with those used in recent stock assessments which can be referred to for additional details (Smart et al. 2024a; Smart et al. 2024b).

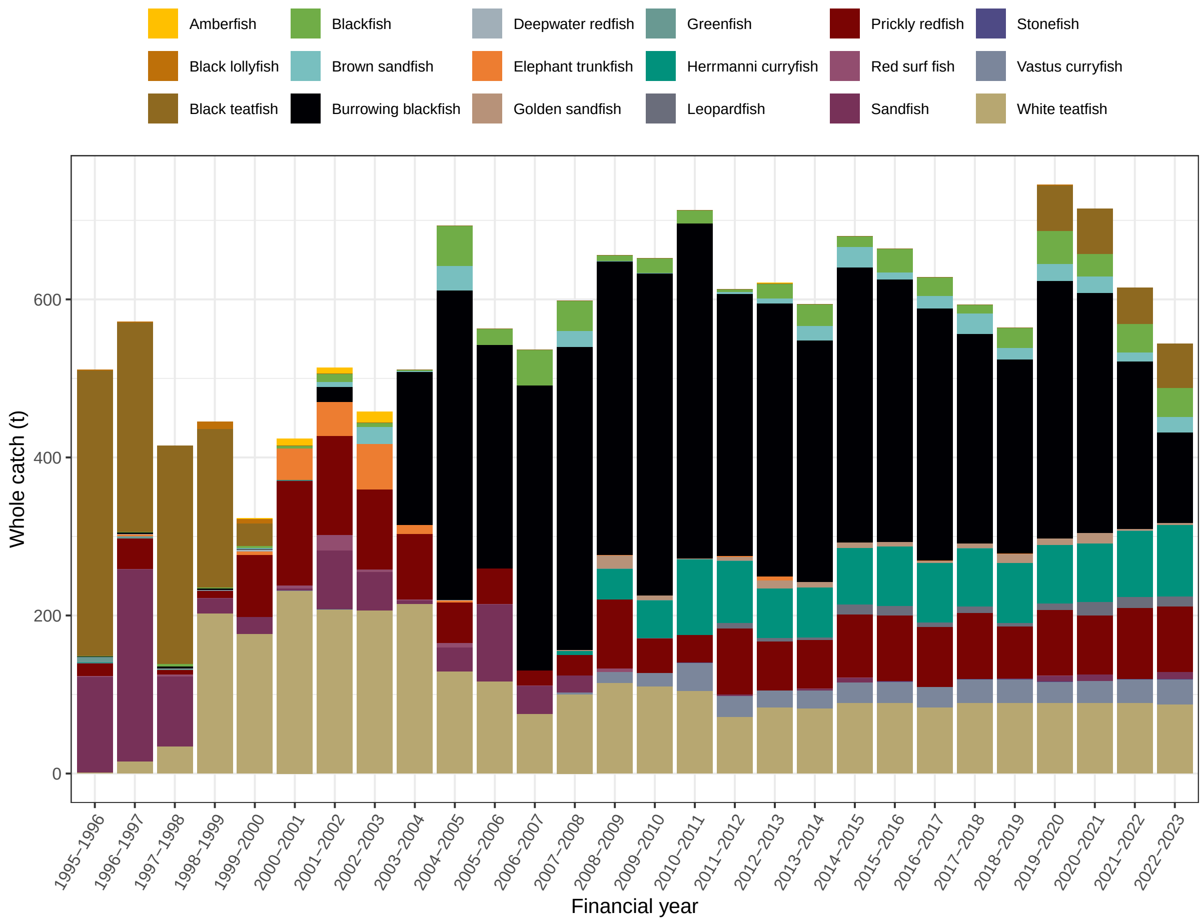

Figure 2.2: Retained catch (whole weight) of all sea cucumber species. Product weights were scaled to whole weight based on the product conversion factors from (Murphy et al. 2021).

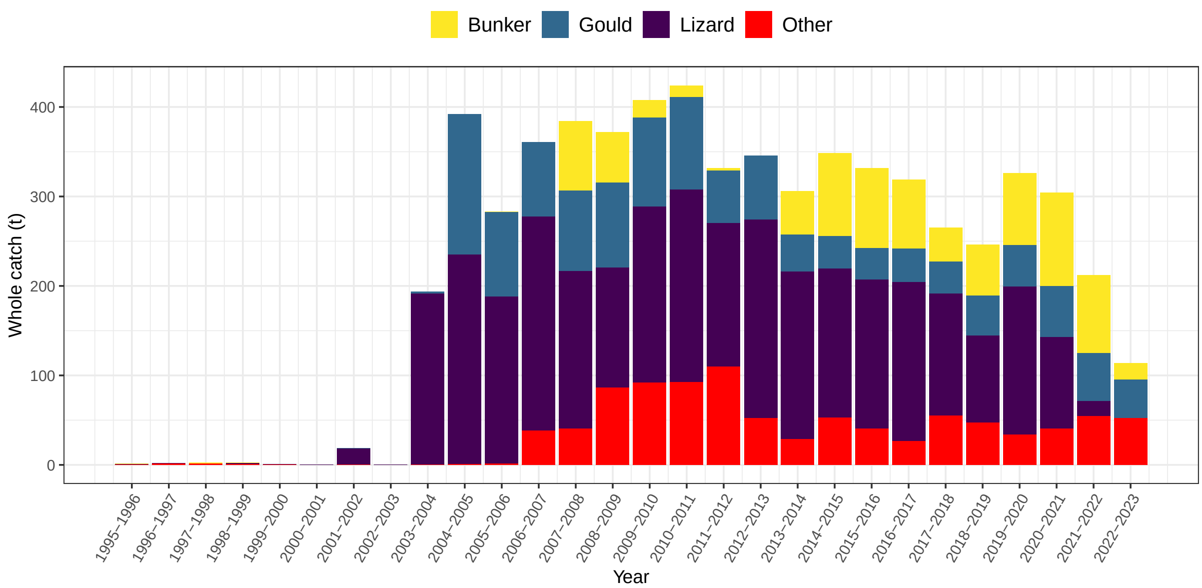

Figure 2.3: Retained catch (whole weight) of burrowing blackfish across the three burrowing blackfish zones. Product weights were scaled to whole weight based on the product conversion factors from (Murphy et al. 2021).

2.2.3 Biological information

The level of biological information varies for each species and often had a large degree of uncertainty. Details on how this was handled is presented in Section 2.4 while the biological values used for each species are given in Appendix A.

2.2.4 Stock assessments

A WTO condition addressed in this report was to incorporate recent biomass surveys (Koopman et al. 2019; Koopman et al. 2023; Koopman et al. 2024a) and stock assessments (Smart et al. 2024a; Smart et al. 2024b) into the MSE. The modelled species included were burrowing blackfish from the Gould and Bunker BBZ, prickly redfish, herrmanni curryfish and vastus curryfish. This was accomplished by using the outputs of the Stock Synthesis models from these stock assessments to build the operating model. These stock assessments considered catch, catch rates, length compositions and estimates of absolute biomass. The stock assessments (Smart et al. 2024a; Smart et al. 2024b) were highly reliant on biomass estimates from recent surveys and their use as a foundation of the operating models therefore incorporates these biomass estimates into the MSE.

The most appropriate biological parameters identified and used in the stock assessment models were incorporated in the MSE with suitable uncertainty ranges. Unfished recruitment R_0 and the depletion (aka relative biomass) at the end of the historical period were specified using the Stock Synthesis estimates for each species. R_0 was specified using the point estimate of the models (*openMSE* only considers a single value for this parameter) while depletion was specified as a uniform distribution that spanned the 95% confidence intervals of the spawning biomass estimates from the models. Estimates of fishing mortality and catchability were also included. This process effectively conditions the operating model such that the historical fishery (1995 - 2023) corresponds with the relative spawning biomass trajectory estimated in the stock assessments, along with their corresponding uncertainty. The future projections of the MSE therefore start at these stock levels and consider current stock status in the results. They are also informed by levels of fishing mortality estimated by these models.

2.3 MSE design

The MSE design captured the relevant management for each species such that the results were informative and supported by data. A selection of catch limit rules, size limit rules, rotational harvest rules, and stock assessment models were applied to each species' OM such that current management was tested as well as alternative management for comparison. The treatment of each OM falls into one of four species groups described in Sections 2.3.1 – 2.3.4.

2.3.1 Burrowing blackfish

Burrowing blackfish are one of the most economically important species in the QSCF and have a unique habitat preference for deep inter-reefal benthic habitats requiring separate management to the rest of the fishery (Skewes et al. 2014; Skewes 2023). Burrowing blackfish are primarily harvested in three zones: Lizard, Gould and Bunker, with each BBZ capped by a zone-specific catch trigger. There are large distances between each of the zones (Figure 1.3) 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 of the dynamics of neighbouring populations, allowing for spatial management (MSC 2022). Some preliminary genetics work supports this (Williamson et. al, in prep.). Burrowing blackfish are also found in low densities throughout the GBR and may be caught as bycatch in other areas but this catch makes up less than 15% of the burrowing blackfish catch (Figure 2.3). Each burrowing blackfish zone is represented by a separate OM. The OMs contain two areas, one for the fishery area and the other for the surrounding green zones that are closed to fishing but likely contribute to recruitment.

A stock assessment for burrowing blackfish was undertaken concurrently with this MSE report (Smart et al. 2024a). These results were used to condition the operating models for each BBZ, as per Section 2.2.4. The stock assessments also indicated that the Lizard reef stock has experienced repeated low recruitment leading to ongoing stock depletion in the absence of fishing. This phenomenon was out-of-scope for this MSE, so no Lizard reef results are presented in this report (see Section 4.3.1 for further details).

This MSE was designed to test the current harvest strategy in the QSCF as well as offer alternative methods for comparison. The burrowing blackfish operating models were subject to three types of MPs – catch limits, size limits, and closed-loop stock assessment models with a 60-20 harvest control rule. The MPs are detailed in Section 2.5.

2.3.2 Prickly redfish, herrmanni curryfish, vastus curryfish

Prickly redfish, herrmanni curryfish and vastus curryfish make up a large portion of current retained catch in the QSCF and are tier 2 species harvested according to the 3-year rotational harvest strategy with a trigger limit on catch. A two-area operating model for each species was tested against MPs with catch and size restrictions. One area represented the fishery area and the other represented the surrounding green zones that are closed to fishing but likely contribute to recruitment. A 157-area operating model was tested against MPs with rotational closures – 1 green zone and 156 rotational zones.

Stock assessments and biomass surveys were completed concurrently with this MSE which formed the basis of each species' operating model (Smart et al. 2024b). Similar to burrowing blackfish, these results were used to condition the operating models for each species at the reef-wide level, as per Section 2.2.4. Given the moderate level of data for these species, the non-spatial operating models were also subjected to closed-loop MPs (see Section 2.5 for more information).

2.3.3 Amberfish, blackfish, black teatfish, brown sandfish, golden sandfish, leopardfish, sandfish and white teatfish

The third group contains the species that have had significant catch but do not have up-to-date stock assessments: white teatfish, black teatfish, amberfish, blackfish, brown sandfish, golden sandfish, leopardfish and sandfish. The operating models used the average fisher hours each year to produce a relative rate of effort through time. The stock size was manually adjusted to replicate the observed catches. All other settings followed the generic OM described in Section 2.4. There is little biological information to inform growth, maturity, recruitment, movement, natural mortality and current depletion for many of these species. Therefore, a wide range was used for each parameter as appropriate, so that any uncertainty in these parameters was accounted for in the MSE. Where values were known, less uncertainty was specified. The biological parameters, their uncertainty and source(s) are listed in Table A.

All of these species have trigger reference limits or TACs and are subject to the 3-year rotational harvest strategy. A two-area operating model for each species was tested against MPs with catch and size restrictions. A 157-area operating model was tested against MPs with rotational closures. Closed-loop MPs were not applied.

2.3.4 Black lollyfish, deep water redfish, elephant trunkfish, flowerfish, greenfish, pinkfish, snakefish, stonefish, and surf redfish

The final group contains the minor species of the fishery that had such little contribution to the fishery that they were not included in any modelling work: black lollyfish, deep water redfish, elephant trunkfish, flowerfish, greenfish, pinkfish, snakefish, stonefish, and surf redfish. The minor species are discussed in Section 3.1.3.

2.4 Operating models

Single-stock operating models were developed for amberfish, black teatfish, blackfish, brown sandfish, burrowing blackfish, golden sandfish, herrmanni curryfish, leopard fish, prickly redfish, sandfish, vastus curryfish, and white teatfish. The remaining species in the fishery (black lollyfish, deep water redfish, elephant trunkfish, flowerfish, greenfish, pinkfish, snakefish, surf redfish and stonefish) are qualitatively evaluated in Section 3.1.3.

Single-stock operating models were suitable for this fishery since a single fleet type is operating and all operators are subject to the same management arrangements (see https://openmse.com/features-multimse/). In addition, trigger reference levels are set at a species-level and little is known about species interactions. Single-stock operating models likely neglect impacts arising from species interactions or targeting behaviours but are better supported by the limited available data. The multi-species total TAC of the QSCF was also not evaluated due to this model design choice.

Limited information exists on stock size, species biology, and spatial connectivity for sea cucumbers so the operating models included a significant amount of uncertainty. Most parameters were assigned a uniform distribution which encompassed the most likely true values. Preliminary modelling showed that incorporating full uncertainty of biological parameters, reflective of the data limitations and biological nuances, resulted in uninformative projections, so most of the stock values represent a most plausible range.

The operating models comprised of four objects that described the stock dynamics (stock object), the fleet operation (fleet object), the implementation of management (implementation object) and the collection of data (observation object). A generic foundation was built for each object that described the common biology, spatial structure and fishery operation that applied to all species. Then, each object was modified to capture the individuality of each species and combined to create an operating model for each species. The values in the generic stock object were deemed representative of sea cucumber biology and provide adequate uncertainty when little is known about the stock.

2.4.1 Stock object

Growth

Sea cucumbers are known to grow and shrink, especially during a fishing event when they may feel threatened or removed from the water. This makes growth difficult to quantify. In the previous MSE, authors chose to use a linear growth relationship given the suitability of available data, simplicity, and consistency with the von Bertalanffy growth curve in younger ages (Skewes et al. 2014). The default model for individual growth in *openMSE* is the von Bertalanffy growth curve. For simplicity and consistency with the available stock assessments, the von Bertalanffy growth curve was used with the parameters drawn from a uniform distribution reflecting the stock assessments and literature when available. The variance of the growth parameters were set to 0 in the generic stock object.

Maturity

Similar to information on growth, little maturity information is available for sea cucumbers but some information was sourced from Conand (1989) and Williamson et al. in prep. For most species, maturity was assumed to occur approximate to the minimum legal size (MLS) with additional uncertainty specified.

Natural mortality

The natural mortality of sea cucumbers is largely unknown but there are published estimates for some species or suitable values found through previous MSE work (Skewes et al. 2014). The most plausible von Bertalanffy growth parameters, maximum age and published estimates were also provided to the 'Natural mortality tool' developed by Cope et al. (2022) to check consistency among biological parameters. For each species, a uniform range for M was specified and included a wide range of values.

Stock recruitment relationship

A Beverton-Holt stock recruitment relationship was used for all species. The value of the steepness parameter was of great uncertainty but a steepness of 0.3 yielded the most robust results in stock assessment models developed alongside this MSE. This low value describes a stock with low recruitment power when the stock is small. The generic stock object set a uniform steepness range of 0.3 to 0.5. The recruitment process error (recruitment variance) was also informed by stock assessment modelling and set to a uniform range of 0.2 to 0.3, indicating relatively small annual deviations from the Beverton-Holt model. The auto-correlation of the recruitment deviations was set to a uniform range of 0.5 to 0.9 to suggest some influence from environmental conditions.

Virgin recruitment

The virgin recruitment of the operating models used the stock assessment estimates of R_0 when available. Specifying stock size from stock assessment results means that the operating models are informed by the biomass surveys. However, absolute stock size is less important in MSEs since performance of the MPs is usually measured in a relative or standardised way. The warty sea cucumber fishery (*Apostichopus parvimensis*) in California MSE set the number of initial recruits to an arbitrary 100 000 individuals (Hordyk et al. 2017). When a stock assessment was not available, an appropriate R_0 value was tuned such that simulated catches from the historical period spool up approximated real catches.

Depletion

Given recent concerns about sea cucumber status, the generic stock object specified a lower bound of 0.2 for the 2023 depletion relative to an unfished state. This was used when recent depletion was not available from recent stock assessments. The upper bound was set to 1 which represented a population unaffected by fishing mortality. The wide range is useful to determine how MPs perform under worst-case and best-case scenarios.

MPA closures

The QSCF operates on the GBR where approximately 37% of sea cucumber habitat has been protected by green and yellow zones since 2004. The generic stock object uses a two-area spatial structure with area 1 representing the protected areas (i.e. green zones). The size of area 1 was set to 37% and the proportion of the population in area 1 was conservatively set to 37%. Sea cucumbers are slow moving and mostly sedentary so the probability of staying in the same area was set to 99%. The marine protected area design in the generic stock object creates a closure in area 1 in all years from 2004 to 2023. Therefore, the GBRMP RAP is incorporated into the historical and projected years of the MSE.

Spatial structure

In the QSCF, all species except burrowing blackfish are managed under the RHS so the operating models required extended spatial structure in order to implement the current management. There are 158 zones in the QSCF with 54 areas open in the first rotation year, 52 areas open in the second rotation year and 52 areas open in the third rotation year. The RHS MP required an even number of areas open each year, therefore 156 zones were incorporated in the spatial MPs to represent the RHS.

Despite having 158 areas in the QSCF, there are clear ‘hotspots’ for fishing that are likely most economical for the businesses operating on the fishery. Figure 2.4 shows the effort distribution for prickly red fish where effort is concentrated around Townsville – which is the case for many species.

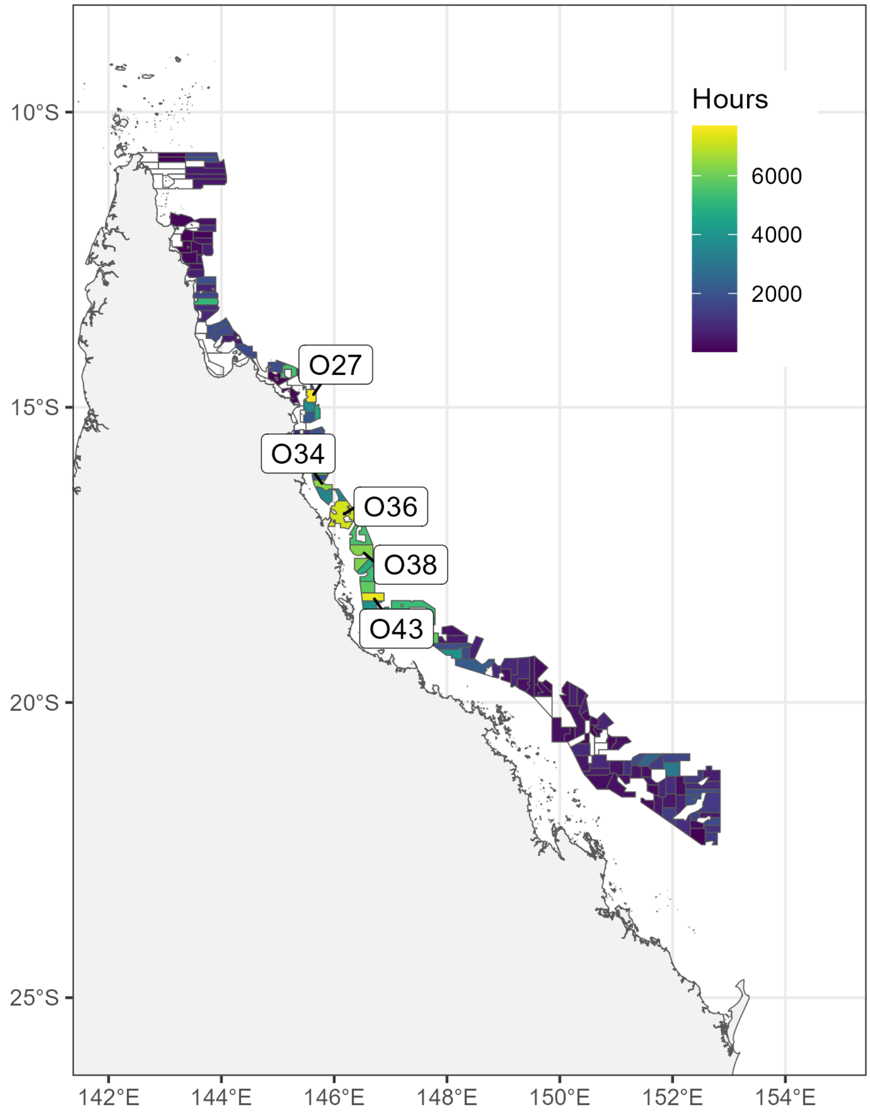

Figure 2.4: Distribution of historical effort from 1995 to 2023 for prickly redfish with the top 5 grids labelled

To replicate the uneven distribution of fishing effort and capture the risk of localised depletion, the areas in the operating models had varying sizes determined at random and consequently, varying biomass in each area. The area design ensured that the open and closed areas were approximately equally distributed throughout the QSCF and each rotation covers approximately equal area. So each year approximately the same amount of biomass is available (i.e., areas open in year 1 had the same approximate biomass available as years 2 and 3).

Due to the computational expense of such a large number of areas (approximately 12 hours for 100 simulations of one operating model), it was decided that non-spatial MPs such as closed-loop MPs would be tested on non-spatial operating models.

Species-specific stock parameters

The species-specific stock dynamics are informed by biological research undertaken by Fishwell Consulting (Koopman et al. 2019; Koopman et al. 2022; Koopman et al. 2024a; Koopman et al. 2023) and others (Conand 1993; Conand 1989; Uthicke et al. 2004), GIS spatial data and stock assessments developed alongside this MSE (Smart et al. 2024a; Smart et al. 2024b). In particular, the stock assessment results are used to inform a plausible range for stock parameters but some are replaced by values that incorporate additional uncertainty where possible. The chosen parameter values for each species are described in Appendix A, Table A.

2.4.2 Fleet object

Fishing effort

The relative changes in fleet dynamics is provided through either fishing effort or fishing mortality. In data poor fisheries, fishing effort may be the number of boats or number of trips or some other effort proxy. If available, the apical fishing mortality rate (F, rate of the most vulnerable age class) may be provided. For species without an up-to-date stock assessment, the total fisher hours over a year was summed to produce a relative rate of effort through time. An upper and lower bound were determined by scaling the upper bound by 120% and lower bound by 80%. For the species with current stock assessments, the estimated fishing mortality time series was used to set the relative effort through time. No additional intra-annual variability in fishing mortality rate was added.

Catchability

Catchability informs the relationship between fishing effort and catch. Much like R_0 the absolute value is less important since performance of the MPs was measured in a relative or standardised way. For non-assessment species, catchability was estimated during specification of the operating model such that the fishing trend and depletion for each simulation was aligned. For species with a stock assessment, the catchability parameter from the stock assessment was tuned to match the historical catch levels. This was required as catchability from Stock Synthesis refers to vulnerable biomass defined by an MLS. However, the MLS was not specified in the *openMSE* OMs so that this could be tested as an MP. Tuning the catchability so that the OM F and catch matched the historical values addressed this. No temporal trend in catchability was implemented. No intra-annual variability was implemented.

Selectivity and retention

The selectivity was set relative to the length-at-maturity. *openMSE* uses two parameters to describe a logistic selectivity curve: the length-at-5%-selected (*L5*) and the length-at-100%-selected (*LFS*). *LR5* was fixed between 10 and 30% of the length-at-maturity while *LFR* was set between 50 and 70% of the length-at-maturity. Retention is set equal to selectivity so there are no discards given the hand harvest nature of the fishery. While species specific minimum legal sizes (MLS) are used in the fishery, this generic approach was used instead rather than specifying these MLS individually. This allowed different MLS relative to length-at-maturity to be tested as MPs, identifying whether increasing an MLS may be beneficial for each species.

Spatial targeting

The spatial targeting was set to the default value of 1 for all areas which distributes fishing effort proportional to legal size biomass in each area.

2.4.3 Observation object

The generic observation model was used from *openMSE*.

Catch and effort sampling

A coefficient of variation between 0.1 and 0.3 was specified for the observation error around catch and effort. For each simulation, a bias value was drawn from a lognormal distribution with mean 1 and CV of 0.1 to represent systematically skewed observational bias (e.g. under reporting or illegal activities).

Catch composition

Length and age compositions do not play a major role in the current fishery and were not used in any potential MPs so these settings were not used.

Biological sampling

Bias in biological samples was not explored in this MSE so these settings were not used.

Surveys and indices of abundance

A coefficient of variation between 0.1 and 0.3 was specified for the observation error around relative abundance indices. A coefficient of variation between 0.2 and 0.5 was specified for the observation error around absolute abundance.

2.4.4 Implementation object

Catch

The fraction of the TAC caught each year was set according to the level of species targeting. Tier 1 species and target Tier 2 species were set at 1 to indicate that the TAC or trigger level would be caught each year. All remaining species that are caught opportunistically had a uniform distribution of 0.2 to 1 set to represent that a catch trigger (expressed as a TAC in *openMSE*) may not be caught. The coefficient of variation on this fraction was set to 0.

Size limits

The size limit implementation was set with a 10% variation of the recommended size limit so the mean retained size varied between simulations. This represents a situation where a undersize animals may be retained given that sea cucumbers can change in length.

2.5 Management procedures

Catch restrictions

The QSCF has catch trigger limits implemented for all species listed in the harvest strategy, with the exception of black teatfish and white teatfish which are managed via a TAC (Table 1.2). However, if a catch trigger is breached for a species or stock then that trigger becomes a TAC in the following fishing season (Fisheries Queensland 2021). Given this minor distinction, catch triggers were applied as TACs in this MSE with the potential for under catches to occur for non-target species, as described in Section 2.4.4. Therefore, in this report the term 'TAC' is used to describe both actual TACs and catch triggers depending on the species being discussed.

MSE best practice advises against testing specific TAC values and rather the MSE should test a rule for defining the TAC. So, in line with how the current TACs were set, an average catch based MP (*TAC*) calculates the catch from the last 10 years of the historical period and sets a TAC at the mean catch level. The TAC MP implements these TACs for every year in the projected fishery. Since the operating models include simulations with varying dynamics, the magnitude of the historical population is different for each simulation. Therefore, the prescribed TAC is different in each simulation. This method of setting a TAC was used accordingly in the spatial and non-spatial MPs.

Size limits

Minimum legal sizes (MLS) are implemented in the QSCF at a length greater than length-at-maturity such that the individuals have an opportunity to reproduce before harvest. Size limits were tested for each species that sets the minimum legal size to length-at-maturity. This method of setting a MLS was used accordingly in the spatial and non-spatial MPs.

Rotational closures

Most species in the QSCF are subject to the rotational harvest strategy. Each area is open every three years but effort is distributed non-homogeneously across open areas according to distance to port and known spatial distribution of economically valuable species. The RHS MPs emulate the fishery behaviour by opening areas every three years and spreading effort proportional to the biomass in each zone through a 18 day TAE. The combination of areas open each year is approximately equal but each area is randomly allocated a size and matching proportion of total biomass. Different RHS MPs use a combination of catch and size restrictions.

Closed-loop MPs

At the time of publication, stock assessments have been completed for six species in the QSCF: black teatfish, white teatfish, burrowing blackfish, prickly redfish, herrmanni curryfish and vastus curryfish. The harvest strategy outlines the decision rules for setting a sustainable harvest are based on a 'hockey-stick' approach (see Figure 1.1). *openMSE* does not support a closed-loop Stock Synthesis MP (or a similar integrated age-structured model) so the current stock assessment schematic was not tested in this MSE.

Alternatively, the delay-difference model used in the burrowing blackfish, prickly redfish, herrmanni curryfish and vastus curryfish stock assessments were replicated with the DDSS MP. Recent stock assessment work showed this model produced similar results to Stock Synthesis (Smart et al. 2024a; Smart et al. 2024b). DDSS_6020 applied a delay-difference model paired with a 60-20 harvest control rule. The delay-difference model is similar to the DDUST model applied in Smart et al. (2024a) and Smart et al. (2024b) but without the capability to include biomass survey data. The MP conducted an automated stock assessment every year of the projection and implemented the appropriate TAC as per the 60-20 'hockey stick'.

Alternative management

Alternative MPs were implemented to see how they compare against the PMs. Some of these MPs were pre-built to *openMSE* while all other MPs were customised for this report.

FMSYref was applied to all two-area operating models to provide a reference level for maximum sustainable yield (MSY). FMSYref uses perfect information about the operating model and is not a viable MP to use in reality.

The TAC_HIGH MP sets the TAC at three times the mean historical catch of the last 10 years. This MP aims to depict a scenario where the biomass is poorly understood and has been overestimated or the fishing mortality rate is actually much higher than the operating models specified. TAC_HIGH pushes the limits of TAC management to showcase the effect of a poorly specified TAC.

The ICI MP adjusts the TAC based on the value of the catch rate index in the current year relative to the time series mean and standard error. If the catch rate index is less than the lower bound of the confidence interval of mean historical index then the TAC is reduced by 25% and if the index is greater than the upper bound of the confidence interval of mean historical index then the TAC is increased by 5%. Otherwise, the TAC is unchanged.

Different size restrictions were also tested. MLS_75 sets the minimum legal size to 75% of length-at-maturity and MLS_125 sets the minimum legal size to 125% of length-at-maturity. For some species, these MPs are true to current management.

Table 2.1: Look-up table for management procedures from the *openMSE* package and custom management procedures that reflect the QSCF harvest strategy

Acronym	Description
TAC	The mean catch of the final 10 historical years is calculated and used to set a constant catch limit (TAC).
TAC_HIGH	Three times the mean catch of the final 10 historical years is calculated and used to set a constant catch limit (TAC).
TAC_MLS_100	The mean catch of the final 10 historical years is calculated and used to set a constant catch limit (TAC). The selectivity is set to length at maturity (LR5, LFR).
MLS_100	The selectivity is set to length at maturity (LR5, LFR).
MLS_75	The selectivity is set to 75% of length at maturity (LR5, LFR).
MLS_125	The selectivity is set to 125% of length at maturity (LR5, LFR).
ICI	'Index confidence interval' adjusts TAC based on the value of the index in the current year relative to the time series mean and standard error. If the index is less than the lower bound of the confidence interval of mean historical index then the TAC is reduced by 25% and if the index is greater than the upper bound of the confidence interval of mean historical index then the TAC is increased by 5%. Otherwise, the TAC is unchanged.
FMSYref	FMSYref assumes perfect information about F_{MSY} (F_{MSY} is taken from the operating model), and sets an effort limit (TAE) so that $F = F_{MSY}$ in each year the MP is applied.
RHS_TAC	The mean catch of the final 10 historical years is calculated and used to set a constant catch limit (TAC). Areas are open and closed according to the RHS with effort distributed proportional to biomass in each open area.
RHS_TAC_HIGH	Three times the mean catch of the final 10 historical years is calculated and used to set a constant catch limit (TAC). Areas are open and closed according to the RHS with effort distributed proportional to biomass in each open area.
RHS_TAC_MLS_100	The selectivity is set to length at maturity (LR5, LFR). The mean catch of the final 10 historical years is calculated and used to set a constant catch limit (TAC). Areas are open and closed according to the RHS with effort distributed proportional to biomass in each open area.

Continued on next page

Table 2.1 – *Continued from previous page*

Acronym	Description
MLS_75	The selectivity is set to 75% of length at maturity (LR5, LFR). Areas are open and closed according to the RHS with effort distributed proportional to biomass in each open area.
MLS_125	The selectivity is set to 125% of length at maturity (LR5, LFR). Areas are open and closed according to the RHS with effort distributed proportional to biomass in each open area.
DDSS_6020	A state-space delay difference stock assessment model with a 60-20 control rule.

2.6 Performance metrics

PMs measure the performance of potential MPs against the management goals of the fishery. The QSCF uses the 'hockey stick' harvest control rule as a guide for balanced outcomes. The 60% target biomass is a theoretical proxy for maximum economic yield as well as a suitable abundance for a healthy stock. Another management goal is to reduce the risk of localised depletion. Sea cucumbers play a vital role in nutrient dispersal and overall health of the marine environment but are quite immobile. Thus, it is important that the fishery does not significantly reduce the footprint of the populations.

Six PMs were defined to evaluate the MPs: the probability of not overfishing (PNOF), the probability of biomass below B_{MSY} (P100), the probability of biomass above the 60% target (Prob_B60), the probability of biomass above the 20% limit (Prob_B20), the probability of localised depletion not occurring (Localised depletion) and the average fraction of maximum sustainable yield obtained (Yield). The first five PMs were evaluated for every projection year of every simulation to balance short term and long term goals. 'Yield' only looked at the last 10 years of the projection to assess the sustainability of the fishery into the future.

Table 2.2: Look-up table for performance metrics from the *openMSE* package and custom performance metrics that reflect the QSCF harvest strategy

Acronym	Description
PNOF	The proportion of projection years the fishing mortality rate is less than the fishing mortality rate resulting in maximum sustainable yield. Also referred to as 'the probability of not overfishing' or $F < F_{\mathrm{MSY}}$.
P100	The proportion of projection years the biomass is less than the biomass resulting in maximum sustainable yield. Also referred to as 'the probability of biomass depletion' or $B < B_{\mathrm{MSY}}$.
Prob_B20	The proportion of projection years the biomass is above 20% of unfished spawning stock biomass averaged across simulations.
Prob_B60	The proportion of projection years the biomass is above 60% of unfished spawning stock biomass averaged across simulations.

Continued on next page

Table 2.2 – *Continued from previous page*

Acronym	Description
Localised depletion	The proportion of areas each year with the biomass above 60% of unfished spawning stock biomass averaged across simulations.
Yield	The fraction of MSY obtained in the last 10 projection years averaged across simulations.

3 Results

3.1 Species specific performance of management procedures

Figures 3.1 – 3.10 show the median biomass trajectory resulting from each MP applied to each of the species. The biomass produced from extended application of the MP is one key metric of performance. The confidence intervals of the biomass trajectories defined by all 100 simulations are shown in Appendix C and demonstrate the cumulative impacts of parameter uncertainty.

The biomass trajectories are split into two periods: the historical period and the projected period. The historical period, from the beginning of the modern fishery to 2023, sets the stage for the impact of historical fishing events and the current biomass status of the species. The projected period showcases the impact of each MP with commencement in 2024. The green zone and fishery zones are separated to show how green zone closures may impact recruitment and biomass. For the two burrowing blackfish models, the green zone and fishery relative biomass trajectories are identical. For the spatial operating models, the 156 fishery areas of the spatial OM are aggregated for plotting purposes.

For some species, there was more than one median historical fishery trajectory. In each case, one trajectory is for the non-spatial operating model and the other is for the 156-area operating model with the fishery areas aggregated. The interaction between the fishery areas, the green zone and the fleet is slightly different for the 156-area operating model so there are minor differences in the relative biomass.

3.1.1 Tier 1 species projected biomass

The black teatfish model mimics the history of heavy fishing and subsequent theorised recovery of the population on the GBR (Figure 3.1). Most tested MPs showed an optimistic future for the black teatfish population with both fishery area and green zones reaching B_{60} around 2030 and continued increasing biomass. FMSYref, on the other hand, caused an immediate drop in biomass and a continued biomass of approximately 35% for the 50 projection years. The MP with the worst biomass outcome was TAC_HIGH which caused the biomass to rapidly approach less than 10% biomass levels in the fishery and less than 20% biomass levels in the green zone. Importantly, the current MP, RHS_TAC_MLS_100, produced a healthy stock in the projection period.

The white teatfish results had a large variation in resultant biomass (Figure 3.2), however, most MPs sustained a relative biomass above 60%. The current MP (RHS_TAC_MLS_125) suggest a continued increasing relative biomass in the projection period. The same MP without a minimum legal size (RHS_TAC) caused continued depletion of the stock. Both MPs with a higher TAC result in a biomass approaching less than 20%.

The two burrowing blackfish stocks, Bunker and Gould, have consistently high relative biomass across all MPs (Figure 3.3 and 3.4). The FMSYref MP implies MSY is obtained at a biomass higher than the target of 60%. The current management applied to both stock results in a relative biomass just 5% below unfished levels.

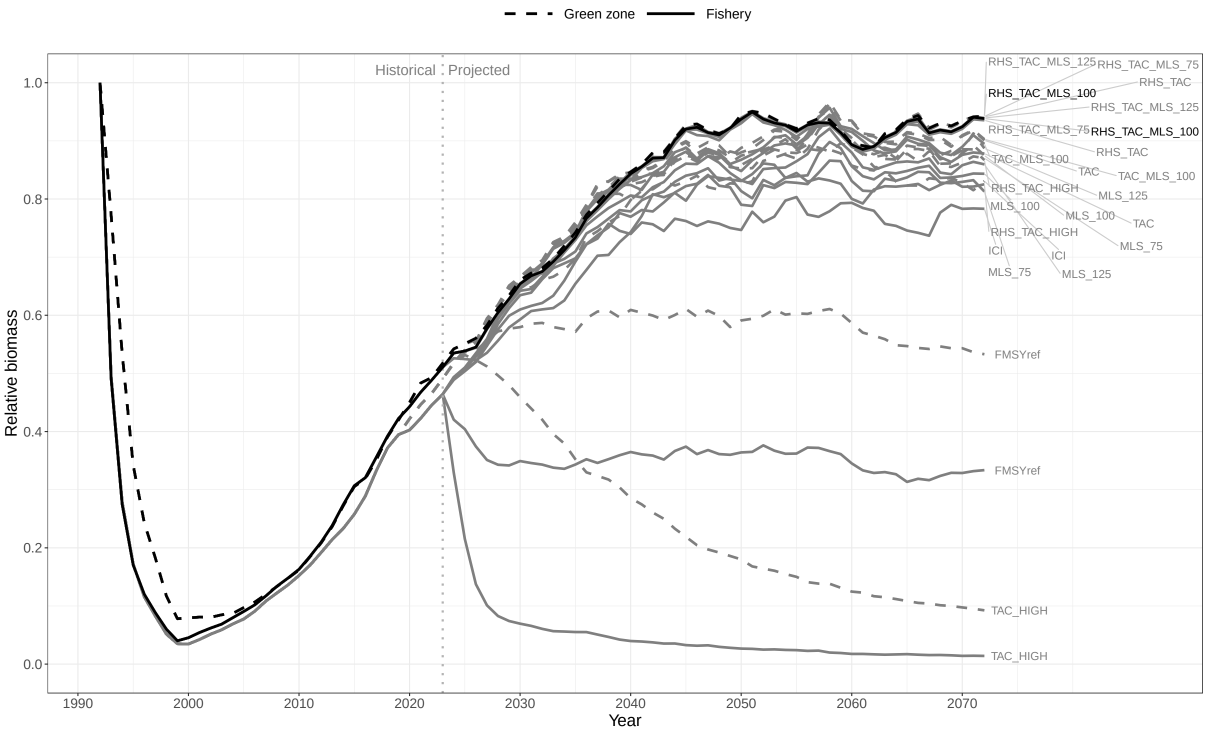

Figure 3.1: Median biomass resulting from each management procedure for black teatfish. The black line indicates the current management procedure. The green zone biomass for each management procedure is indicated with a dashed line.

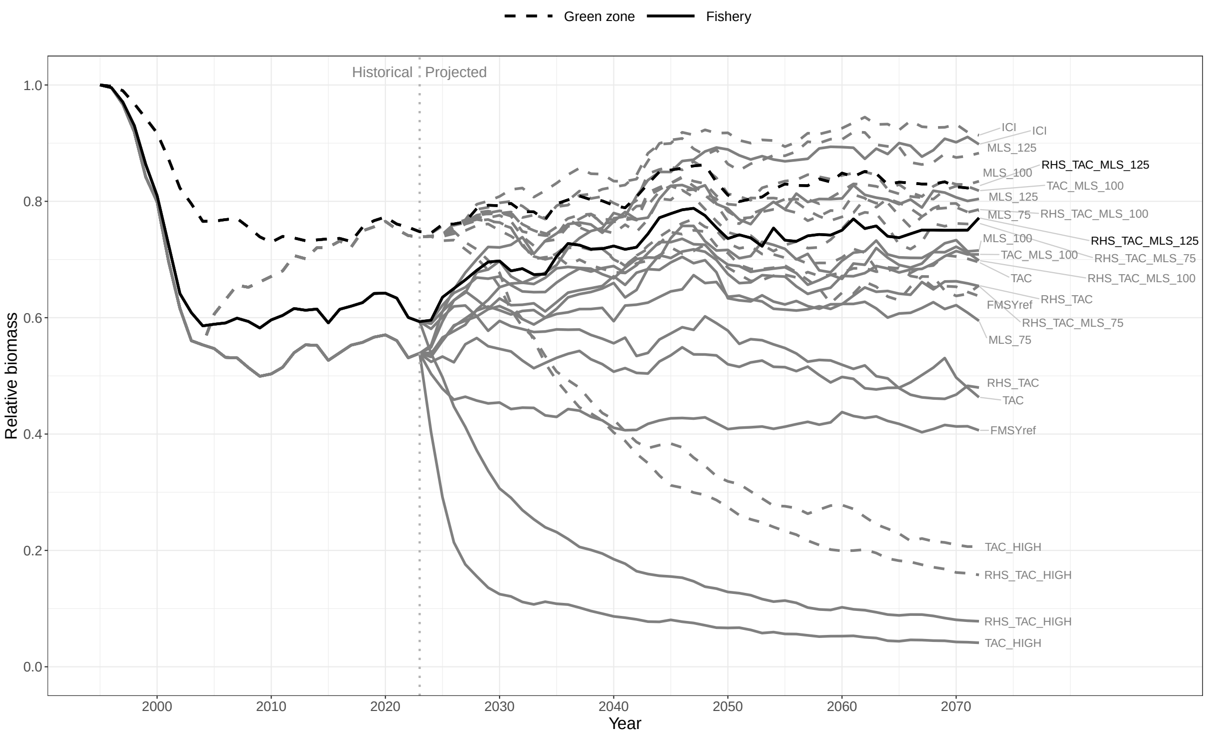

Figure 3.2: Median biomass resulting from each management procedure for white teatfish. The black line indicates the current management procedure. The green zone biomass for each management procedure is indicated with a dashed line.

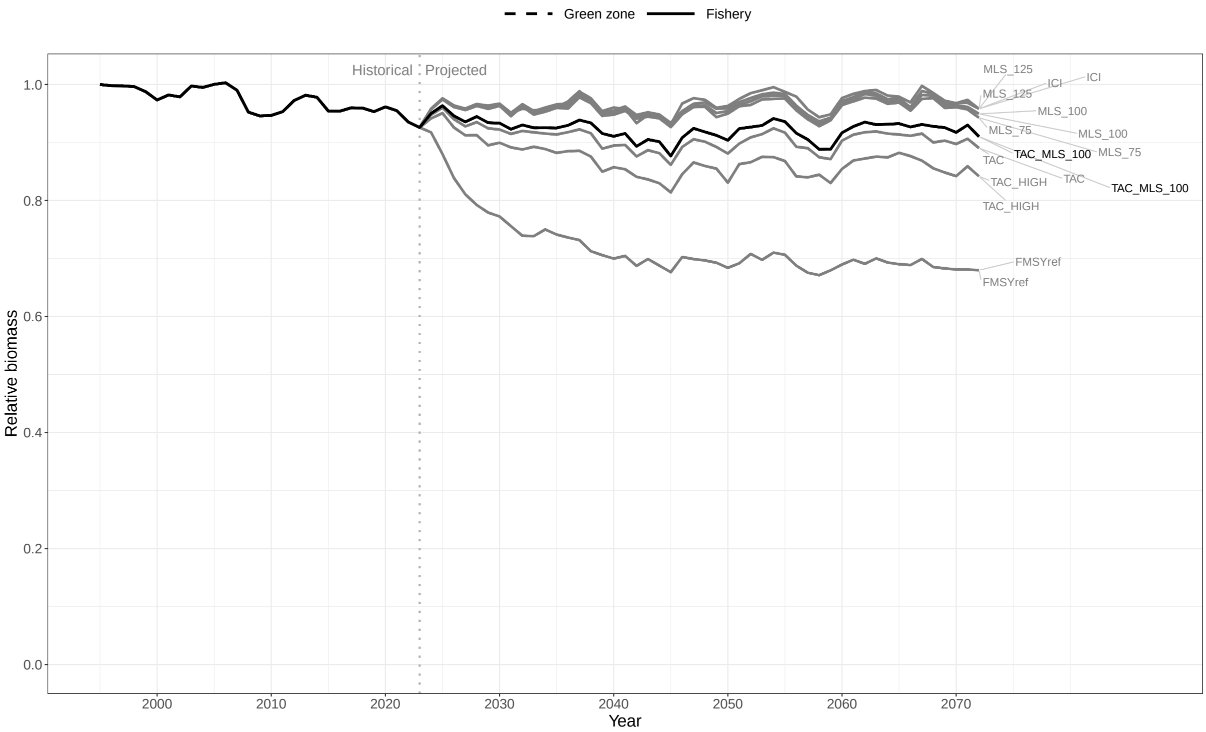

Figure 3.3: Median biomass resulting from each management procedure for burrowing blackfish (Bunker). The black line indicates the current management procedure. The green zone biomass for each management procedure is indicated with a dashed line.

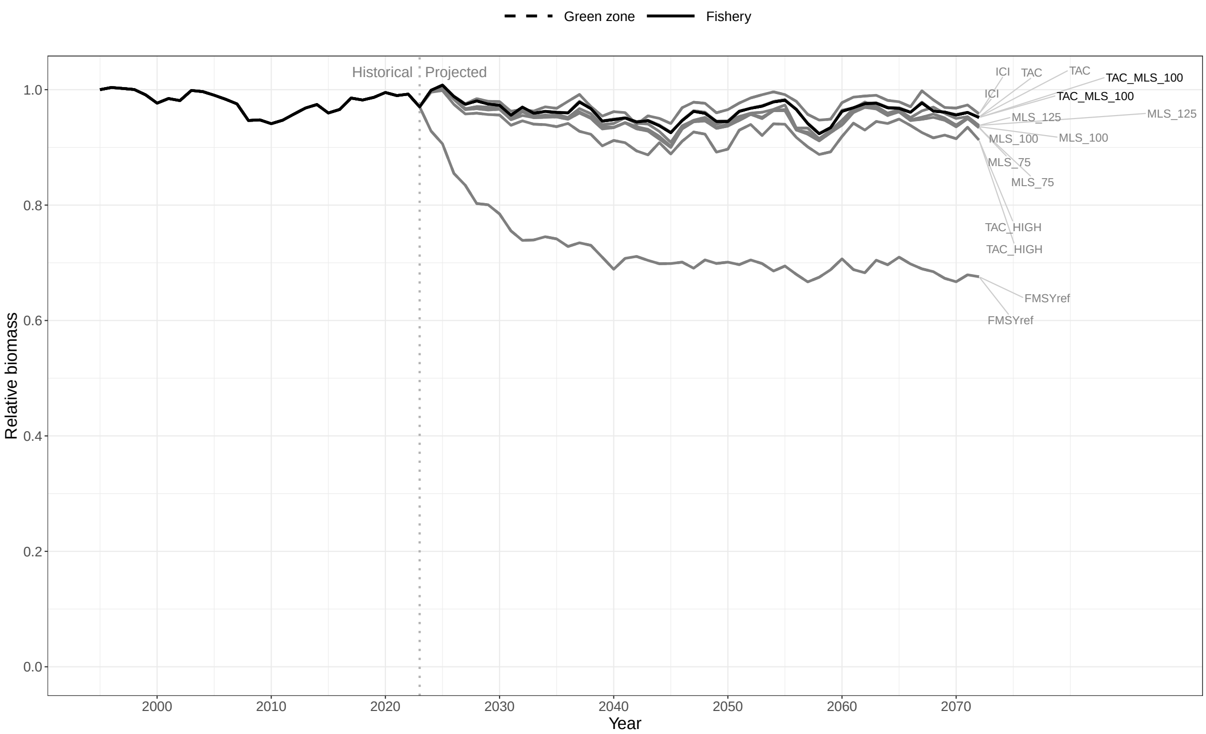

Figure 3.4: Median biomass resulting from each management procedure for burrowing blackfish (Gould). The black line indicates the current management procedure. The green zone biomass for each management procedure is indicated with a dashed line.

3.1.2 Tier 2 species projected biomass

The current MP for every tier 2 species resulted in a projected relative biomass above the target level of 60% in the fishery area and above 80% in the green zone (Figures 3.5 – 3.11). FMSYref consistently fished the population down towards 40% which is an expected biomass level to achieve MSY. For blackfish and sandfish, the MP with a high TAC and no rotational harvest strategy resulted in the lowest relative biomass. Overall, MPs without the rotational harvest strategy resulted in a more depleted population. ICI consistently maintained a stock near virgin levels across all tier 2 species.

Figure 3.5: Median biomass resulting from each management procedure for blackfish. The black line indicates the current management procedure. The green zone biomass for each management procedure is indicated with a dashed line.

Figure 3.6: Median biomass resulting from each management procedure for brown sandfish. The black line indicates the current management procedure. The green zone biomass for each management procedure is indicated with a dashed line.

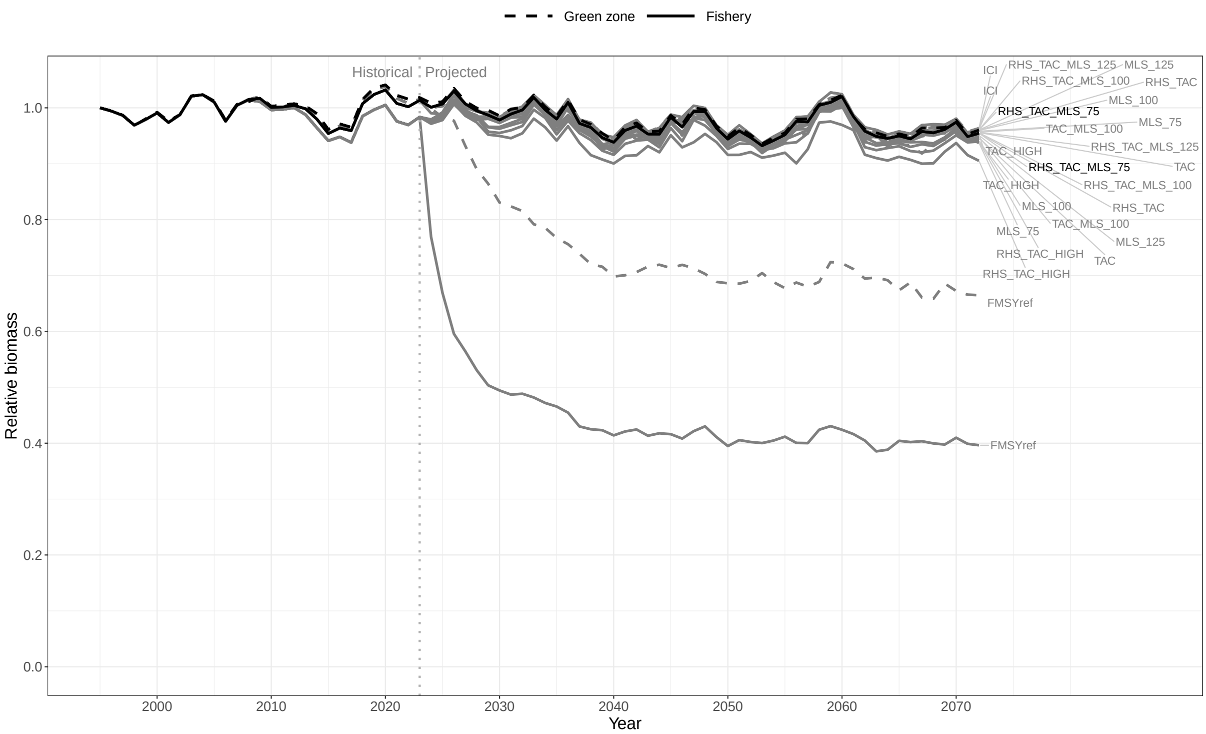

Figure 3.7: Median biomass resulting from each management procedure for golden sandfish. The black line indicates the current management procedure. The green zone biomass for each management procedure is indicated with a dashed line.

Figure 3.8: Median biomass resulting from each management procedure for herrmanni curryfish. The black line indicates the current management procedure. The green zone biomass for each management procedure is indicated with a dashed line.

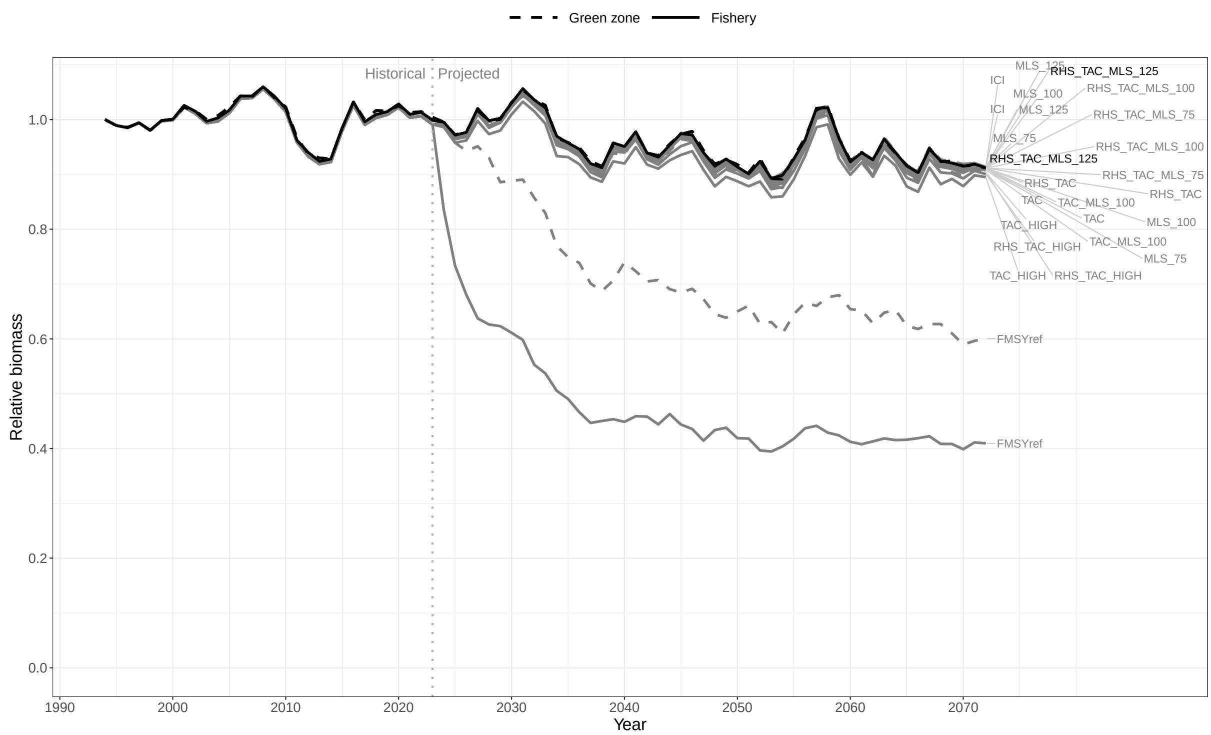

Figure 3.9: Median biomass resulting from each management procedure for prickly redfish. The black line indicates the current management procedure. The green zone biomass for each management procedure is indicated with a dashed line.

Figure 3.10: Median biomass resulting from each management procedure for sandfish. The black line indicates the current management procedure. The green zone biomass for each management procedure is indicated with a dashed line.

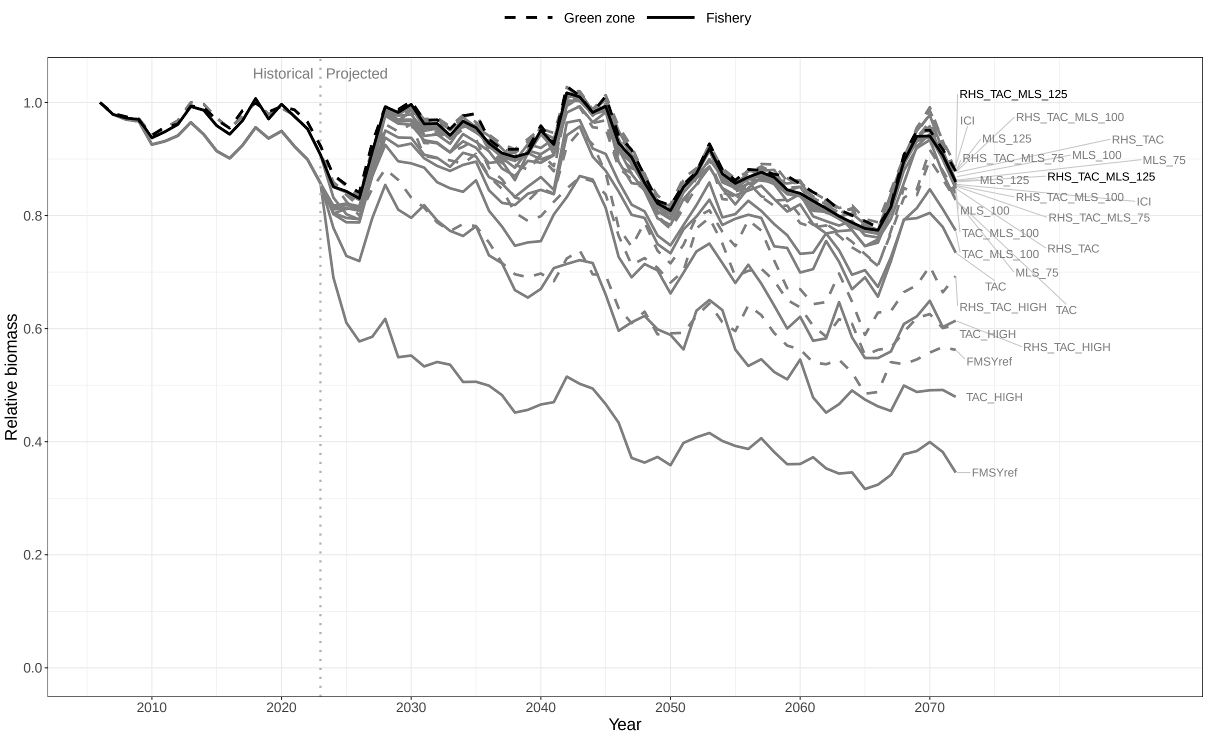

Figure 3.11: Median biomass resulting from each management procedure for vastus curryfish. The black line indicates the current management procedure. The green zone biomass for each management procedure is indicated with a dashed line.

3.1.3 Minor species

Black lollyfish, deep water redfish, elephant trunkfish, flowerfish, greenfish, pinkfish, snakefish, stonefish and surf redfish were not considered in the quantitative modelling of this report. The two main reasons for this omission are the relatively small reported catches over a short period and the lack of biological information. In fact, flowerfish, snakefish and pinkfish have not had any catches reported by the fishery in either the logbooks or buyer returns. Annual catches of the remaining minor species have mostly been well below 10t whole weight and have phased out in the last 20 years. According to industry, around 1995-2000 a broader range of species were caught, due to the decline and closure of the black teatfish fishery, to identify the different market opportunities for sea cucumbers. The appearance and subsequent disappearance of these species from catches occurred as there was no market for them, and therefore industry stopped collecting them.

The biology of these minor species is poorly studied with little information about growth, maturity, natural mortality and reproduction. Biological information is crucial in developing an operating model for an MSE and the amount of uncertainty surrounding these processes would cloud any meaningful outcomes. A previous MSE for the QSCF (Skewes et al. 2014) did not include any of these species and stated that additional biological information was needed for future work to consider them. That research has not occurred and the current information for this MSE is very similar to what was available in 2014.

Additionally and most importantly, the targeting of these species was very low (see Figure 3.12), as indicated by their small proportions of mixed species catches. An argument for the appearance of disappearance of sea cucumber species from catches is that they may have been serially depleted with the fishery switching their targeting between species as abundances decline (Purcell et al. 2014; Eriksson et al. 2015). Indeed, the appearance of such a situation must be treated cautiously. However, the low level of targeting indicates that this was not the case and that these species were only caught opportunistically until it was clear that they were not economically viable. From the information available, it is likely that the current catches provide a low risk to future overfishing and previous catches have not led to overfishing.

The evidence provided here suggests that these species have only been lightly exploited and a very low risk to overfishing is maintained through catches of this magnitude. We therefore conclude that the QSCF does not pose a risk to sustainability for these species.

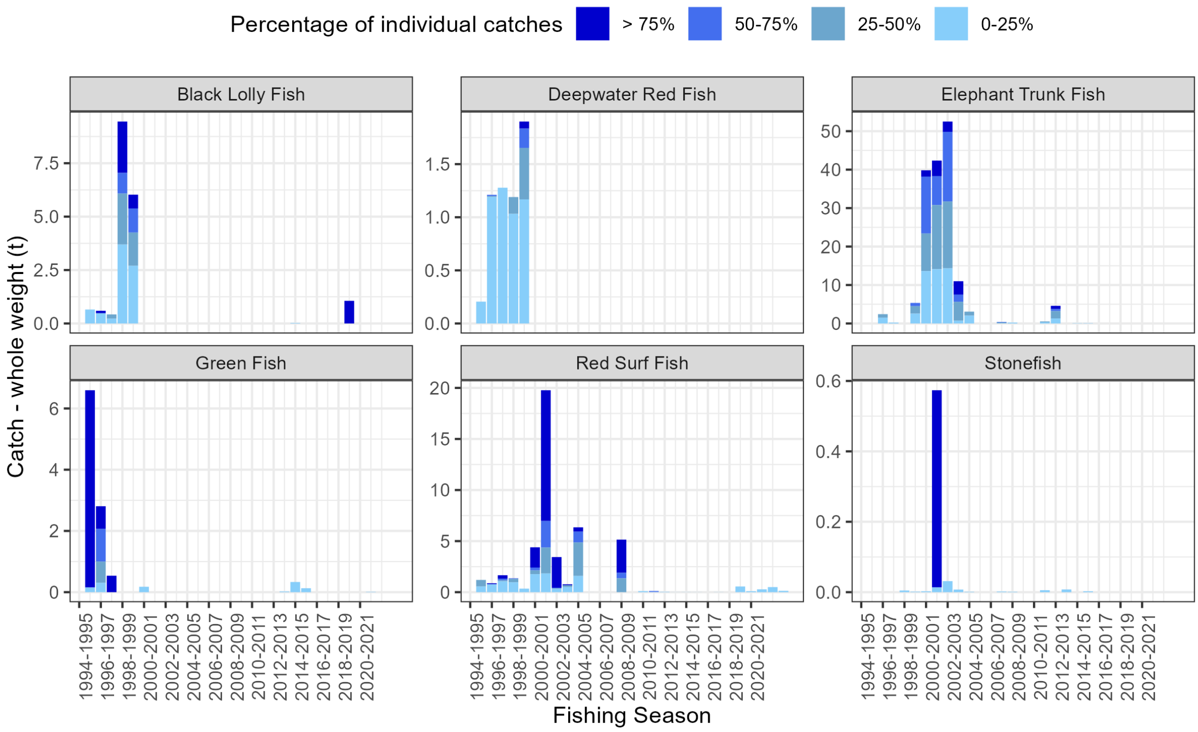

Figure 3.12: Annual catches (whole weight) for six minor species in the QSFC. Coloured stacked bars indicate the total catch from fishing records where the species constituted given proportions of the catch.

3.2 General performance of management procedures

3.2.1 Performance metrics

In this section, each PM as described in Table 2.6 is presented in a tile plot for every combination of MP and species. Red boxes denote the MP most similar to current management for each species. The number in each tile refers to the proportion of simulations that satisfied the metric, unless stated otherwise. For example, in Figure 3.13 the TAC MP applied to white teatfish resulted in 59% of simulations across the projection years applying a fishing mortality less than F_{MSY}.

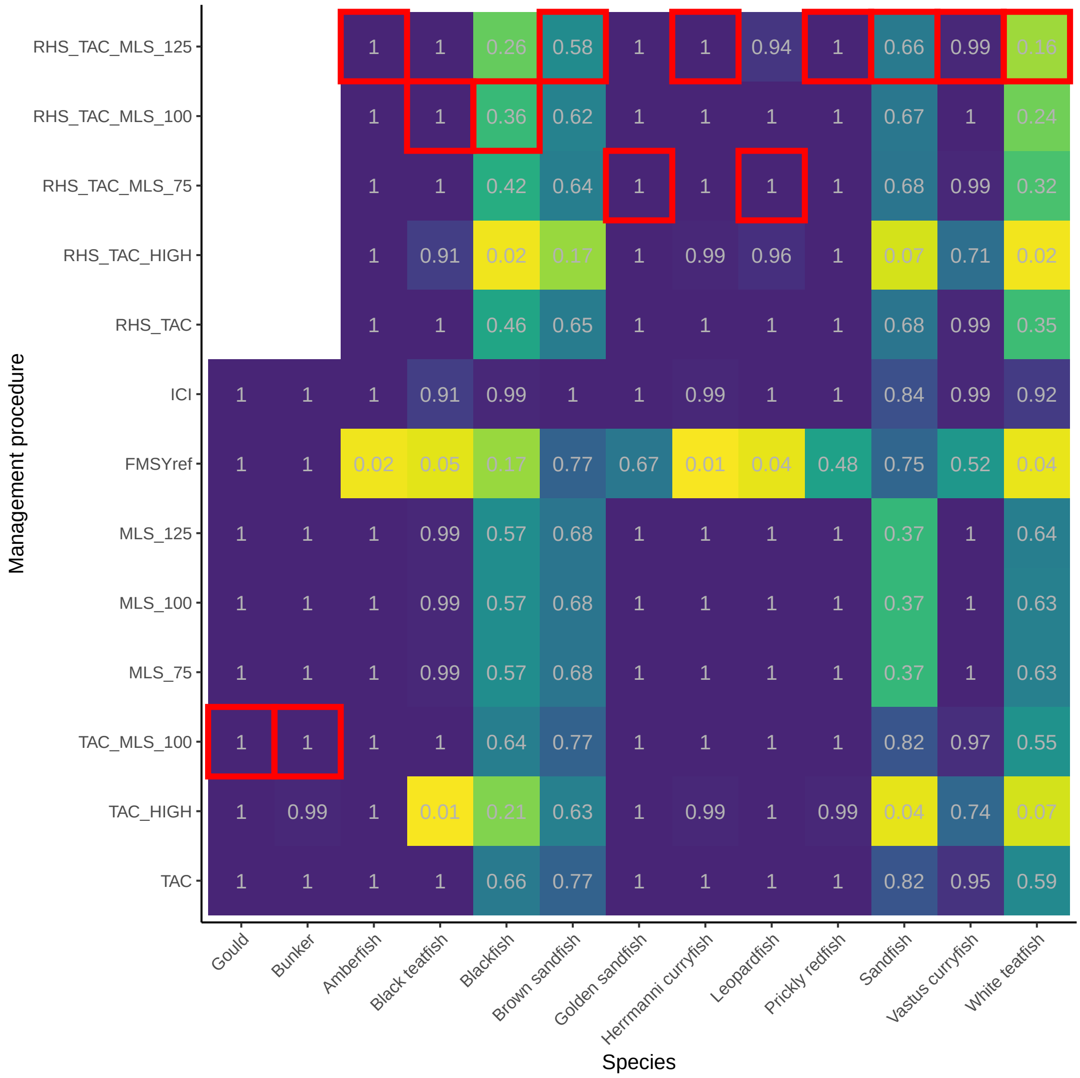

Figure 3.13: Probability of not overfishing ($F < F_{MSY}$). A value of 1 indicates that all simulations had a fishing mortality less than F_{MSY}. A value of 0 indicates that all simulations had a fishing mortality greater than F_{MSY} which has been categorised as overfishing. Red boxes denote the MP most similar to current management for each species.

Figure 3.13 indicates the probability of fishing at a fishing mortality rate less than F_{MSY} – which is often the desirable outcome. The yellow squares highlight the species and MPs that are at risk of over-fishing. A stand out result is that FMSYref performs poorly for most species. In addition, white teatfish and blackfish are at a higher risk of over-fishing for most rotational harvest MPs, in particular RHS_TAC_HIGH which has a TAC three times greater than recent historical harvest and no MLS.

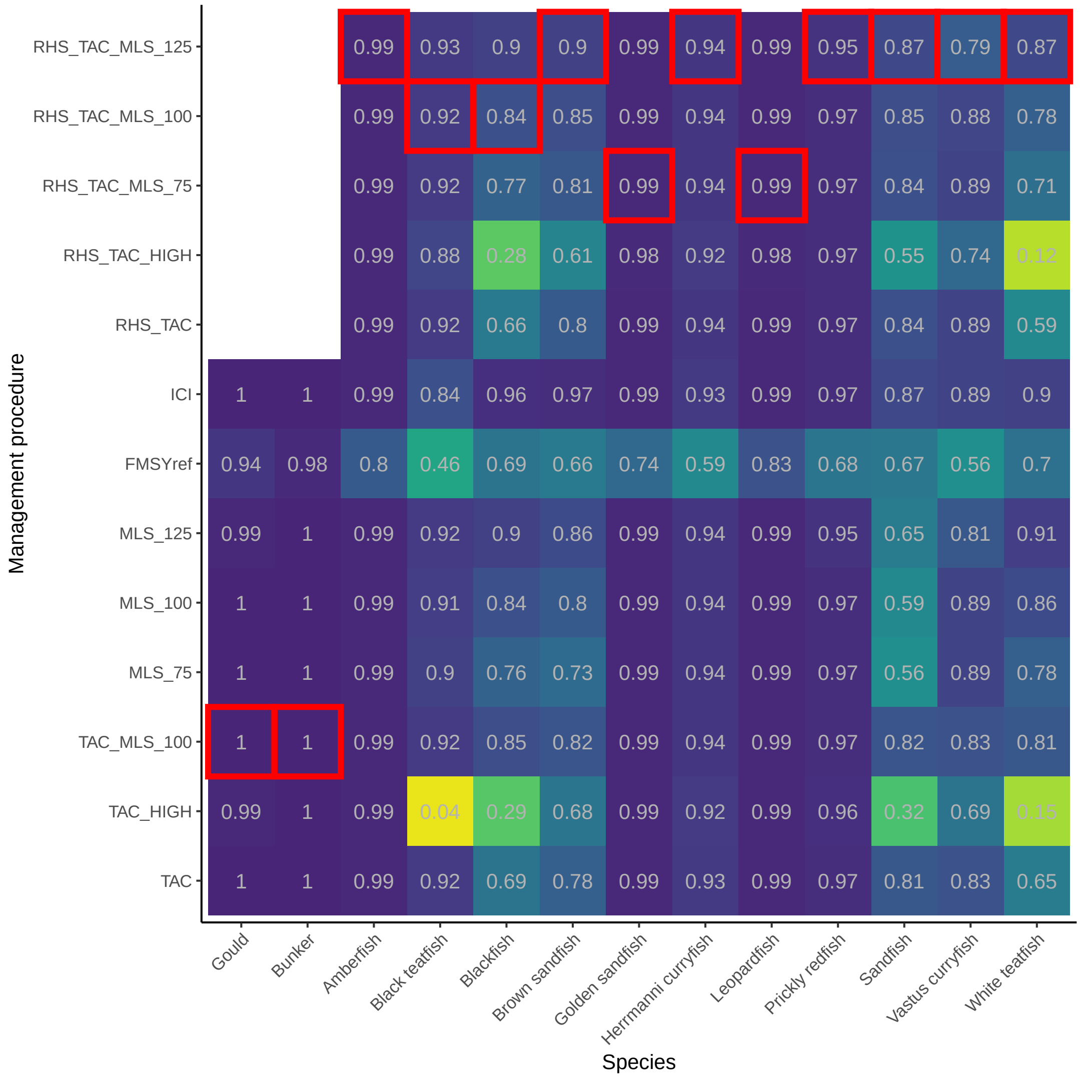

Figure 3.14: Probability of not over-exploitation ($B > B_{MSY}$). A value of 1 indicates that all simulations had a relative biomass greater than B_{MSY}. A value of 0 indicates that all simulations had a relative biomass less than B_{MSY} which has been categorised as over-exploitation. Red boxes denote the management procedure most similar to current management for each species.

Figure 3.14 indicates the probability of sustaining the biomass level above B_{MSY} – which is often the desirable outcome. The yellow squares highlight the species and MPs that are at risk of over-exploitation. A stand out result is when the TAC_HIGH MP is applied to black teatfish, blackfish, sandfish and white teatfish, a majority of simulations become over-exploited. The same is true for the RHS_TAC_HIGH MP but to a lesser extent.

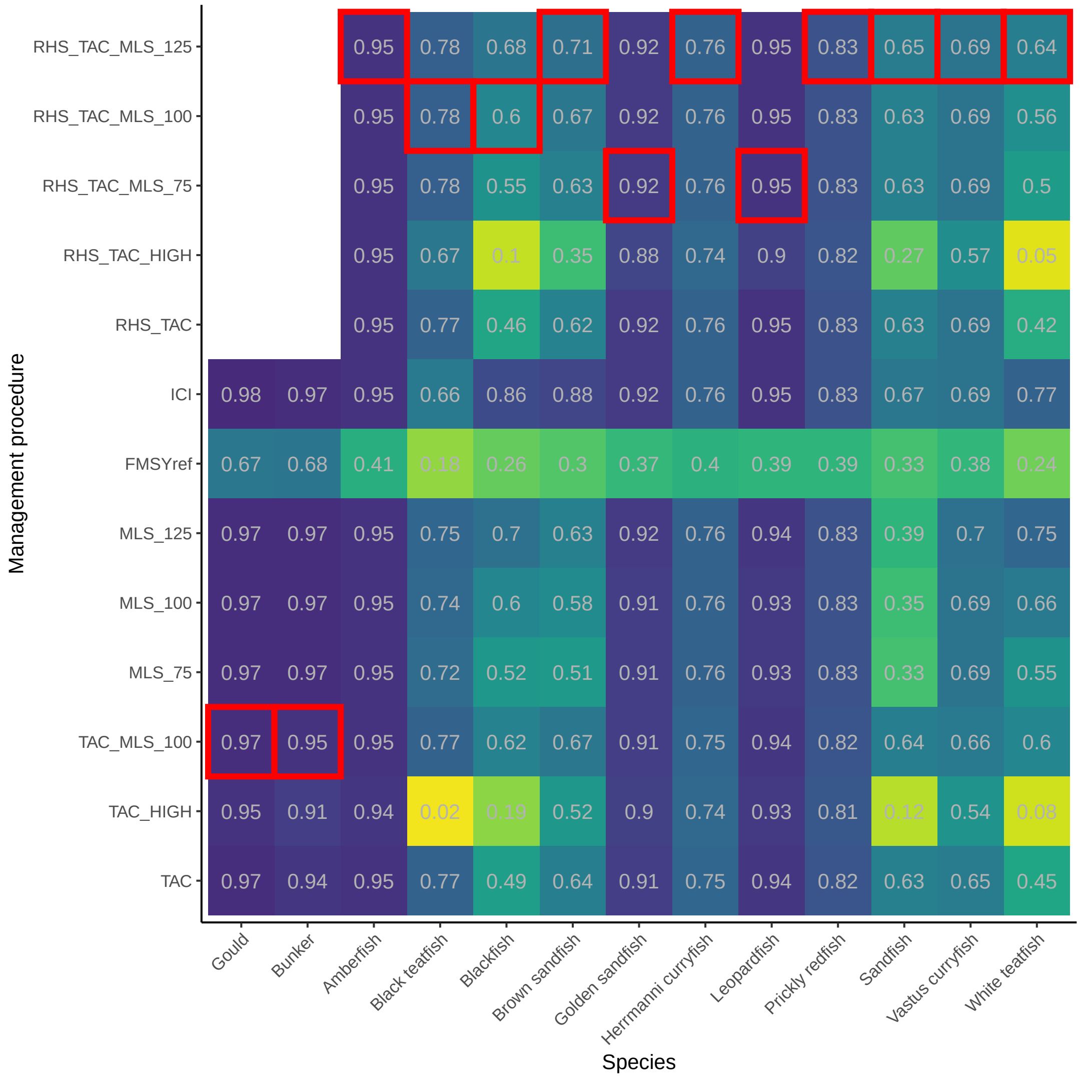

Figure 3.15: The proportion of projection years the entire stock is above 60% of unfished spawning stock biomass averaged across simulations ($B > B_{60}$). A value of 1 indicates that all simulations had a biomass above B_{60}. A value of 0 indicates that no simulations had a biomass above B_{60}. Red boxes denote the management procedure most similar to current management for each species.

Figure 3.15 indicates the probability of sustaining the biomass level above B_{60} – which is the target outlined in the harvest strategy (Fisheries Queensland 2021). The yellow squares highlight the species and MPs that are at risk of over-fishing. A stand out yet uninteresting result is that FMSYref performs poorly for most species since B_{MSY} is less than 60%. The two MPs with increased TACs (TAC_HIGH and RHS_TAC_HIGH) cause the largest risk.

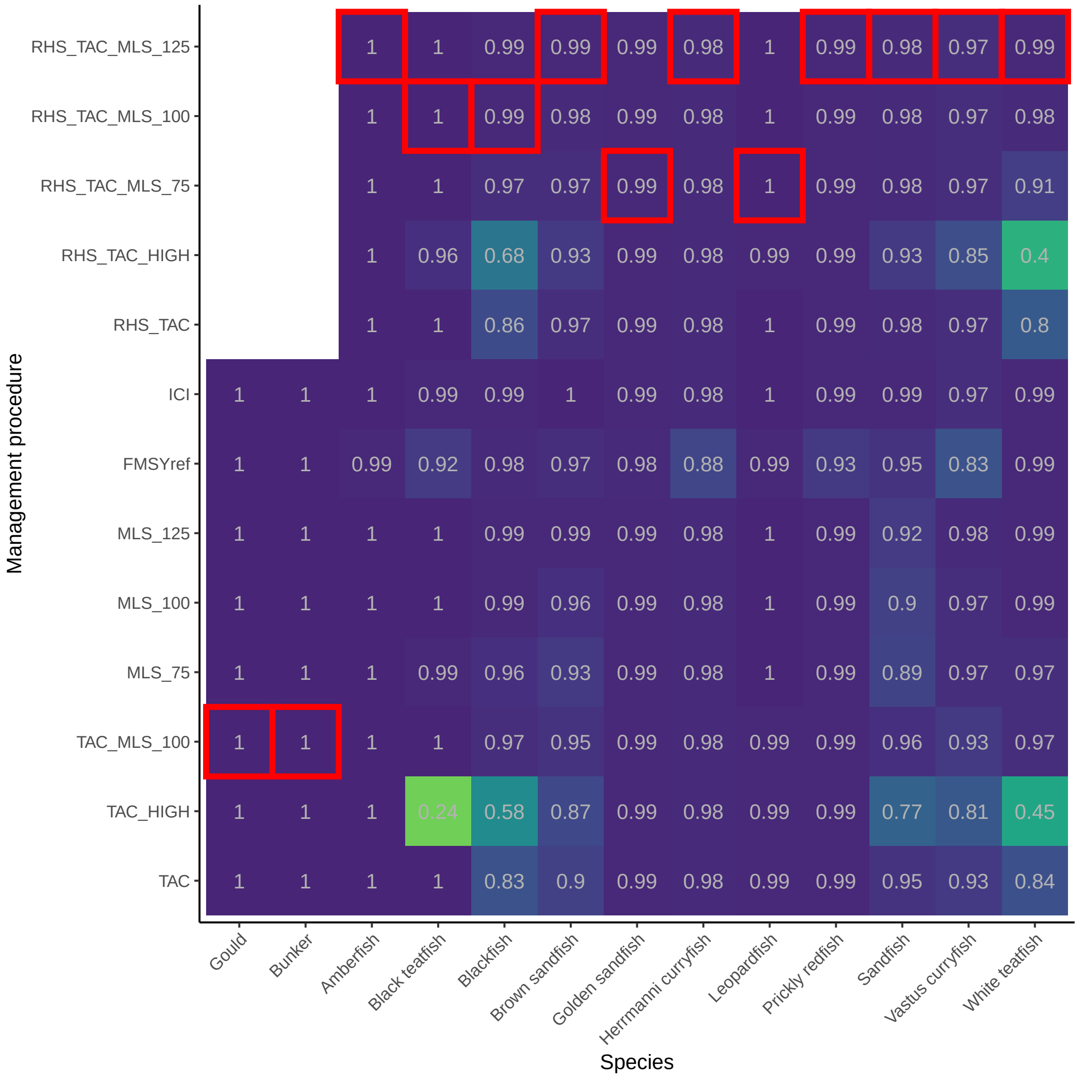

Figure 3.16: The proportion of projection years the entire stock is above 20% of unfished spawning stock biomass averaged across simulations ($B > B_{20}$). A value of 1 indicates that all simulations had a biomass above B_{20}. A value of 0 indicates that no simulations had a biomass above B_{20}. Red boxes denote the management procedure most similar to current management for each species.

Figure 3.16 indicates the probability of sustaining the biomass level above B_{20} – which is the limit outlined in the harvest strategy (Fisheries Queensland 2021). Almost every MP has near 100% of simulations achieving a biomass greater than B_{20}. The MPs that cause concern are TAC_HIGH for black teatfish and white teatfish and RHS_TAC_HIGH for white teatfish.

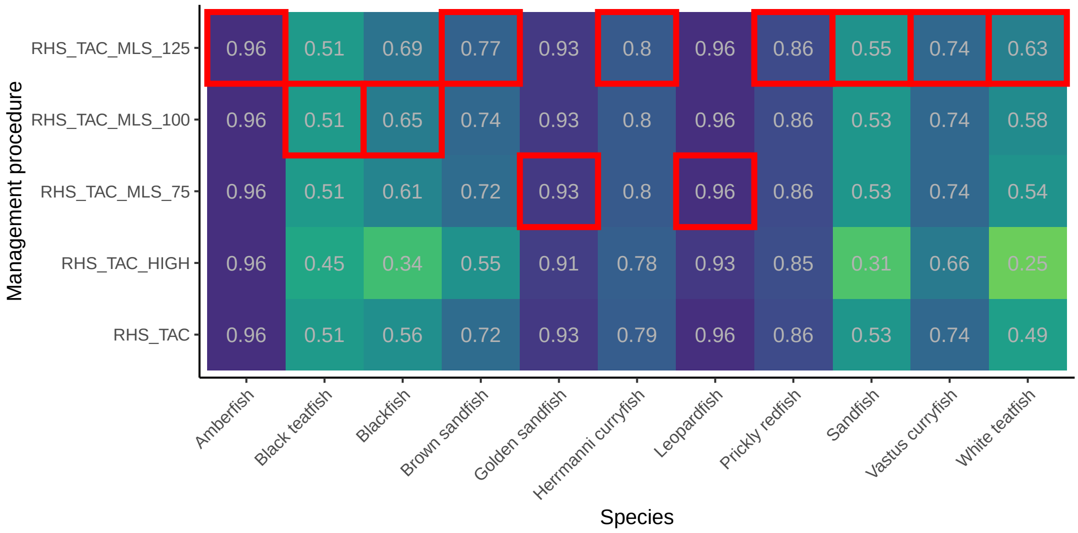

Figure 3.17: The proportion of areas in each projection year the entire stock is above 60% of unfished spawning stock biomass averaged across simulations. The value in the plot refers to the proportion of areas that had a biomass above B_{60}. A value of 1 indicates that all areas in all simulations had a biomass above B_{60}. Red boxes denote the management procedure most similar to current management for each species.

Figure 3.17 indicates the probability of sustaining the biomass level above B_{60} in every area when the rotational harvest strategy is applied. The only poor performing MP was RHS_TAC_HIGH which highlights an increased risk of localised depletion to black teatfish, blackfish, sandfish and white teatfish due to higher catches.

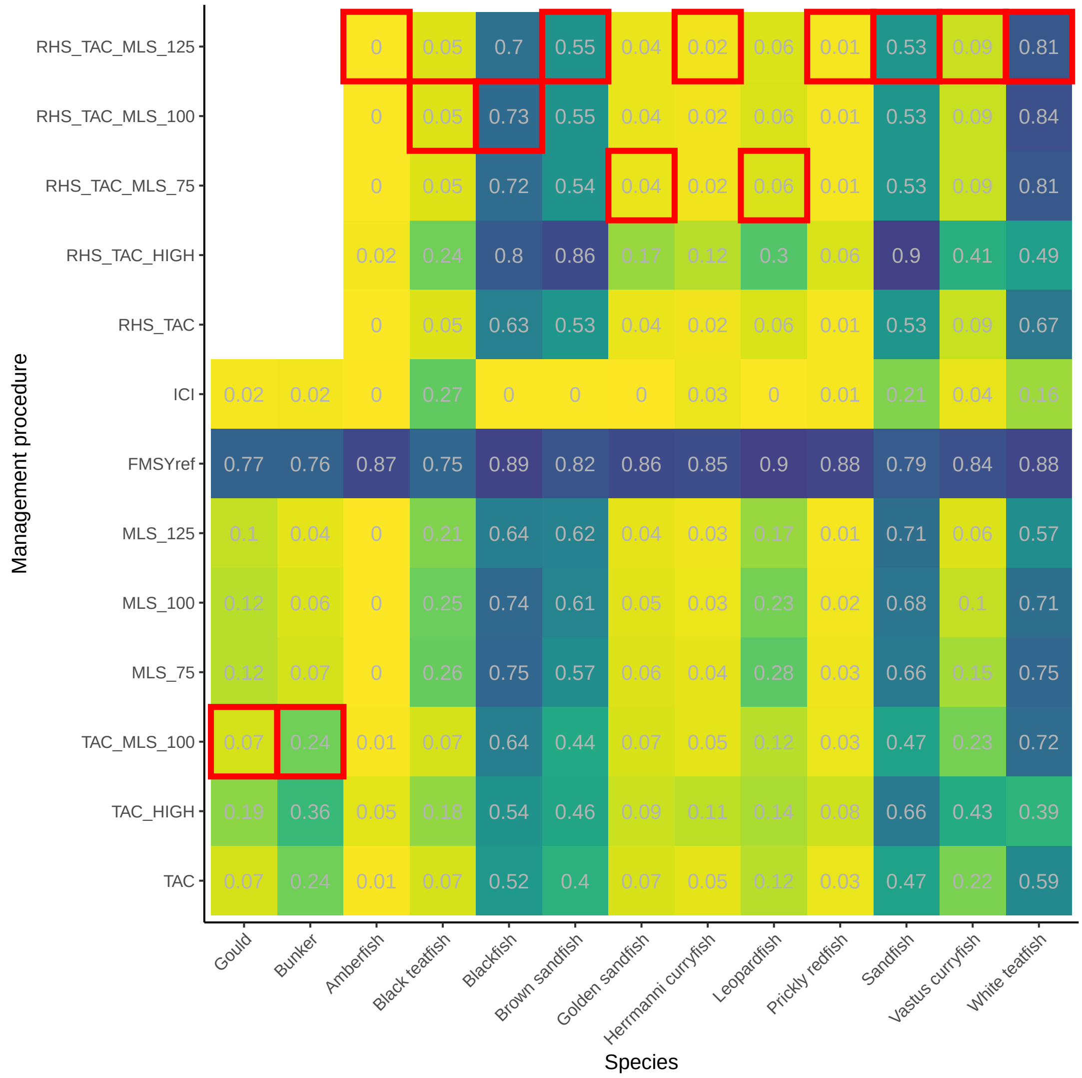

Figure 3.18: The average proportion of MSY retained in the final 10 years of the projection period for each management procedure for each species. A value of 1 indicates that the MP achieved MSY in the final 10 years of the projection. A value of 0 indicates no yield or a very small yield relative to MSY due to rounding. Red boxes denote the management procedure most similar to current management for each species.

Figure 3.18 indicates the average proportion of MSY retained in the final 10 years of the projection period. The yield from FMSYref was obviously near MSY. Yield of blackfish, brown sandfish, sandfish and white teatfish was above 50% of MSY for most MPs. ICI produced very little or no yield for all species, suggesting ICI tended to close the fishery. RHS_TAC_HIGH resulted in higher yields than the non-RHS counterpart, TAC_HIGH.

3.2.2 Trade-off plot

The trade-off plot helps to visualise the inevitable trade-off between abundance and catch when evaluating MPs. Both contribute to the objective of the fishery to ensure sustainability, maintain a healthy ecosystem and obtain maximum economic yield. The ideal, yet unattainable, management would produce high yields and high biomass and would sit in the top left corner of the plot. In reality, MPs with higher yields result in lower biomass. Environmental risk can be attributed to the y-axis where the biomass level is considered. Economic risk can be attributed to the x-axis where yield is considered. The PMs presented in these trade-off plots are from Figures 3.15 and 3.18.

To the left of each trade-off plot is the annual yield across all projection years relative to the MP with the largest yield. This provides an easy comparison of fishery performance under each MP. The current MP is shown in black. The yield metric in the trade-off plots, on the other hand, is the yield obtained in the final 10 years of the projection period relative to MSY.

3.2.2.1 Tier 1 species

For black teatfish, FMSYref and TAC_HIGH pose the highest risk of depletion and all other MPs led to a large relative stock with yield approximately 10% of MSY. For white teatfish, FMSYref, TAC_HIGH and RHS_TAC_HIGH pose the highest risk of depletion and there is large variability between the performance of the other MPs. The current MP is likely the most desirable, leading to high yield and over a 60% probability of exceeding B_{60}.

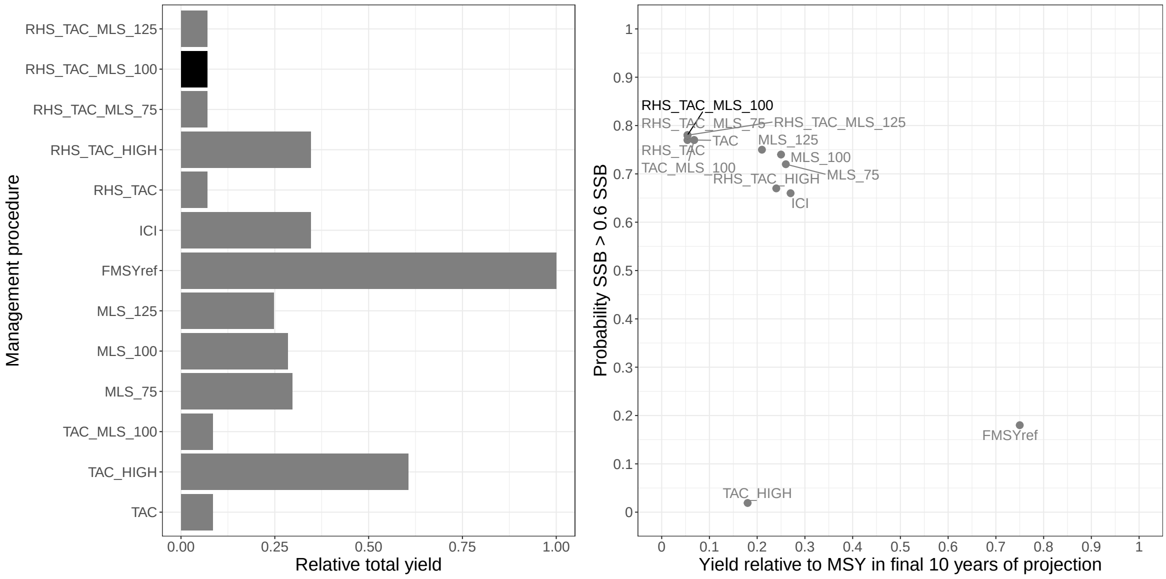

Figure 3.19: Black teatfish trade off between environmental and economic risk. The left panel shows the average yield across all projection years relative to the MP with the highest yield. The right pane shows the trade-off between the Prob_B60 and Yield performance metrics.

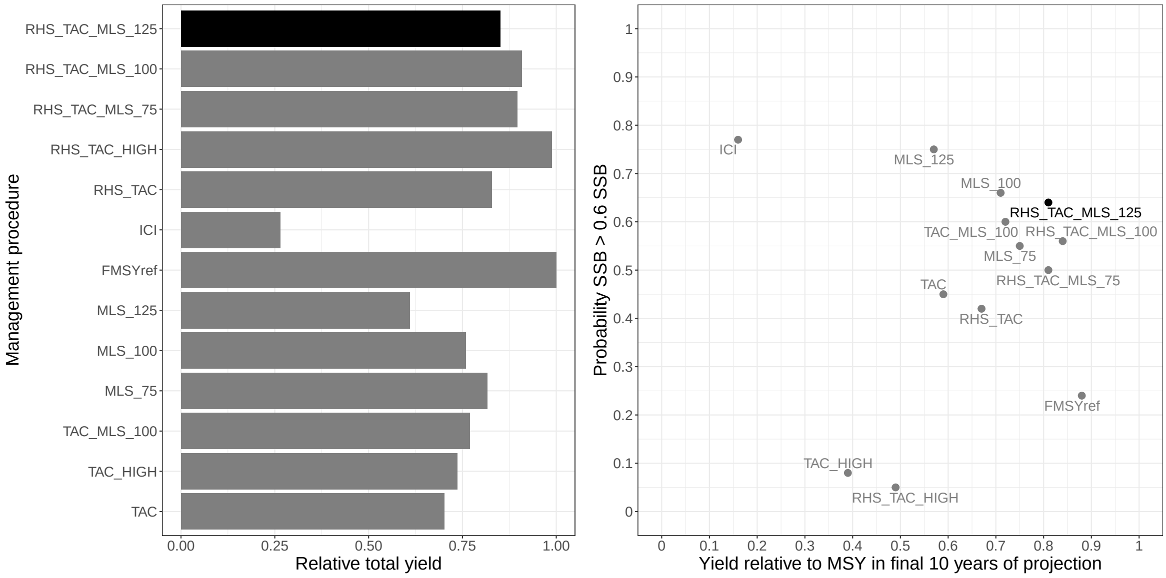

Figure 3.20: White teatfish trade off between environmental and economic risk. The left panel shows the average yield across all projection years relative to the MP with the highest yield. The right pane shows the trade-off between the Prob_B60 and Yield performance metrics.

For the Bunker stock of burrowing blackfish, the current MP led to a high relative biomass and obtained about 30% of the yield from FMSYref. The MP with a high TAC and no MLS produced the second highest yield. For the Gould stock of burrowing blackfish, the current MP also led to a high relative biomass and obtained the second lowest yield, just ahead of ICI. FMSYref produced the highest yield and the MP with a high TAC and no MLS produced the second highest yield.

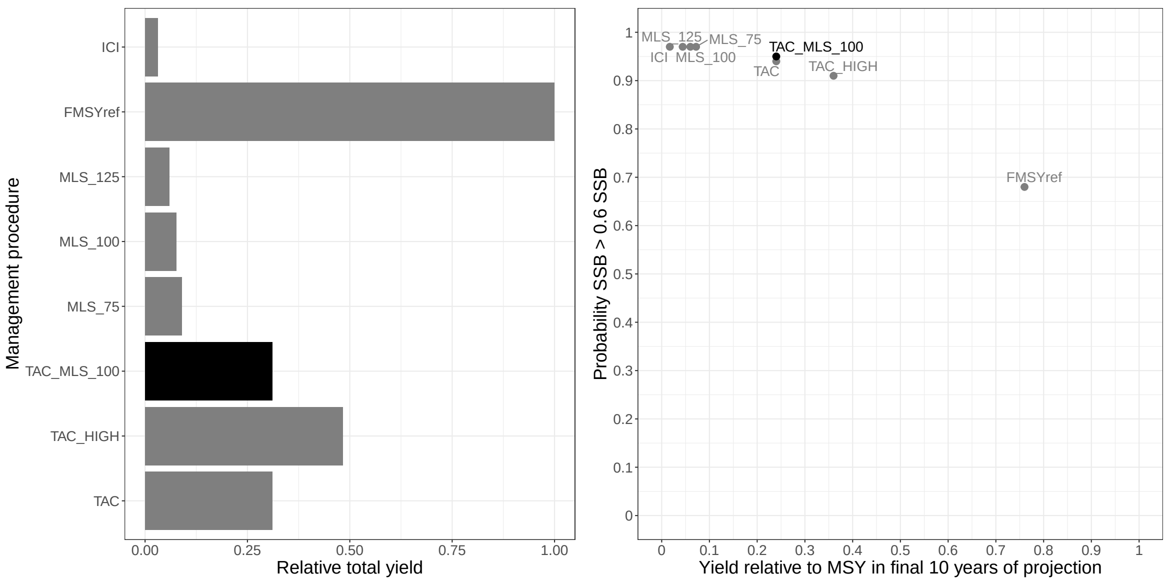

Figure 3.21: Burrowing blackfish (Bunker) trade off between environmental and economic risk. The left panel shows the average yield across all projection years relative to the MP with the highest yield. The right pane shows the trade-off between the Prob_B60 and Yield performance metrics.

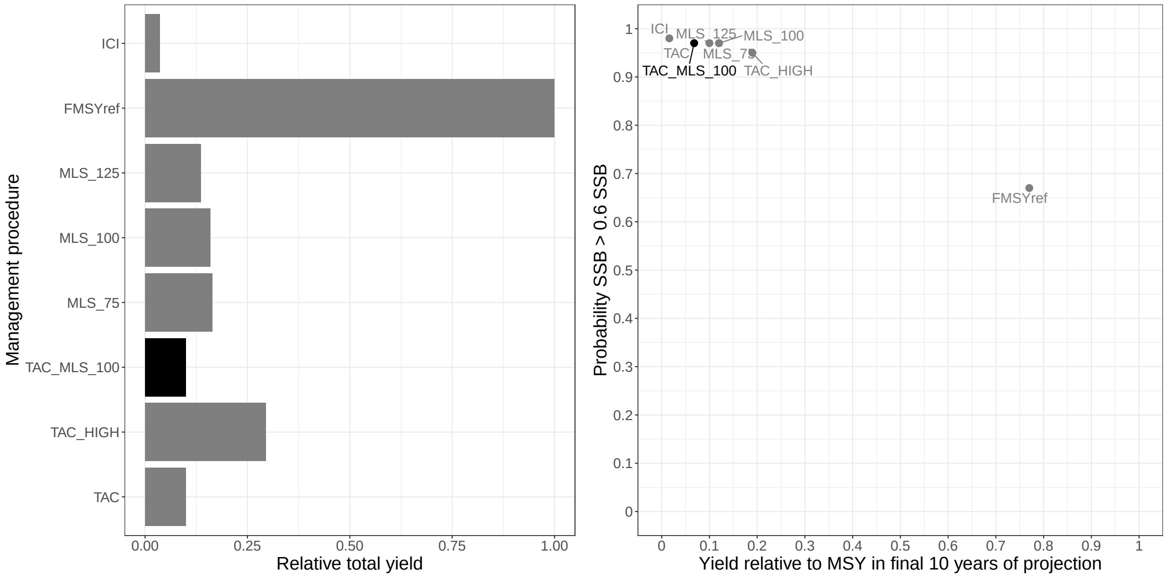

Figure 3.22: Burrowing blackfish (Gould) trade off between environmental and economic risk. The left panel shows the average yield across all projection years relative to the MP with the highest yield. The right pane shows the trade-off between the Prob_B60 and Yield performance metrics.

3.2.2.2 Tier 2 species

The trade-off results for amberfish, prickly redfish, herrmanni curryfish, golden sandfish, and leopardfish (Figures 3.23, 3.25, 3.27, 3.28, and 3.29) show little variation in biomass status due the conservative catches of these species historically. For these species, the current MP performs desirably and there is capacity for increased yield if that was a goal of the fishery. Alternatively, biomass could be increased by implementing MPs with higher MLS and a marginal reduction in yield.

For blackfish, brown sandfish and sandfish, some MPs obtained high yields but resulted in further depletion of the stocks. RHS_TAC_HIGH would quickly produce less relative yield in an extended projection due to a decreasing population size. Blackfish, brown sandfish and sandfish also reveal that MPs with higher MLS resulted in higher biomass with a marginal reduction in yield.

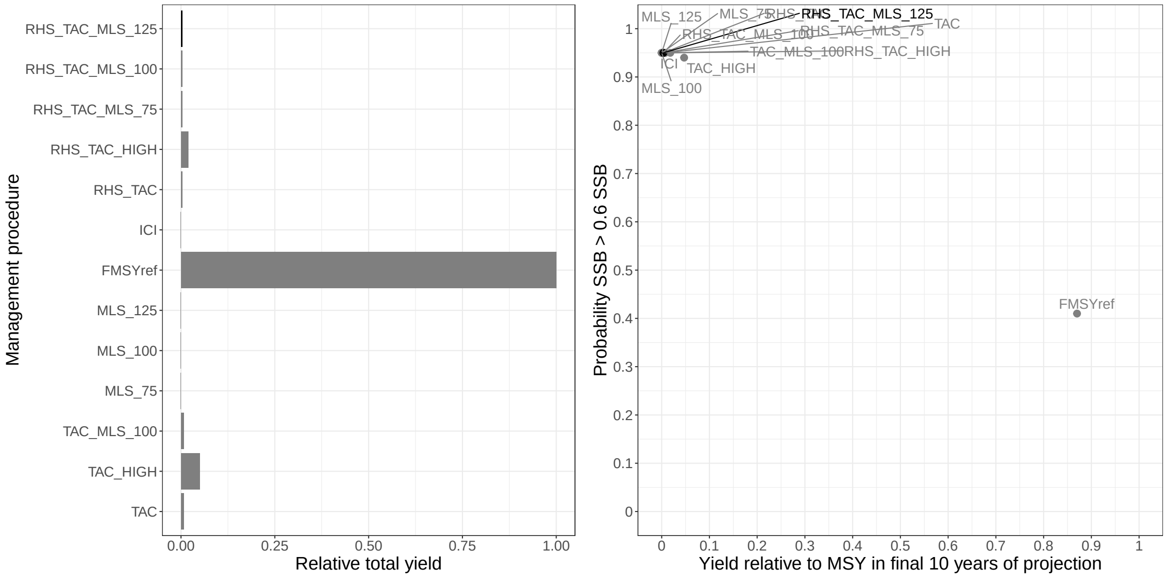

Figure 3.23: Amberfish trade off between biomass and yield relative to MSY

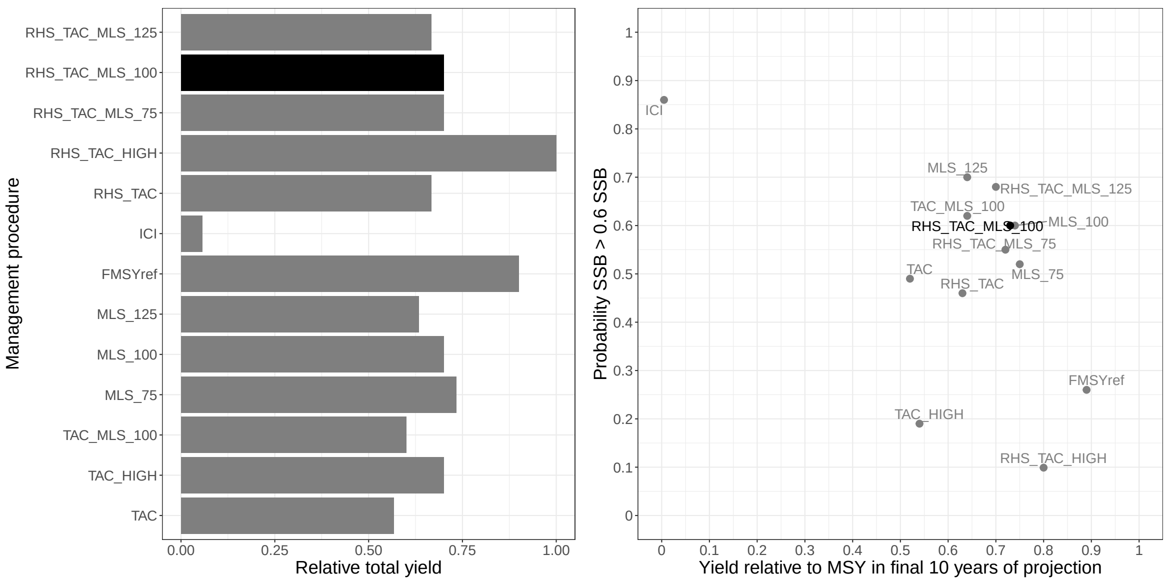

Figure 3.24: Blackfish trade off between biomass and yield relative to MSY

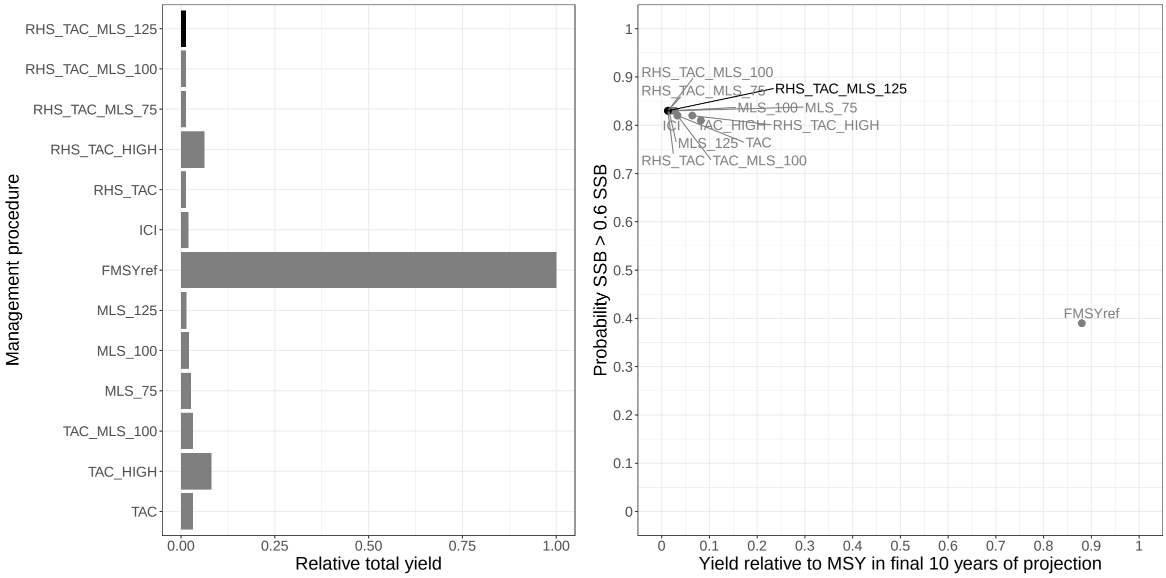

Figure 3.25: Prickly redfish trade off between biomass and yield relative to MSY

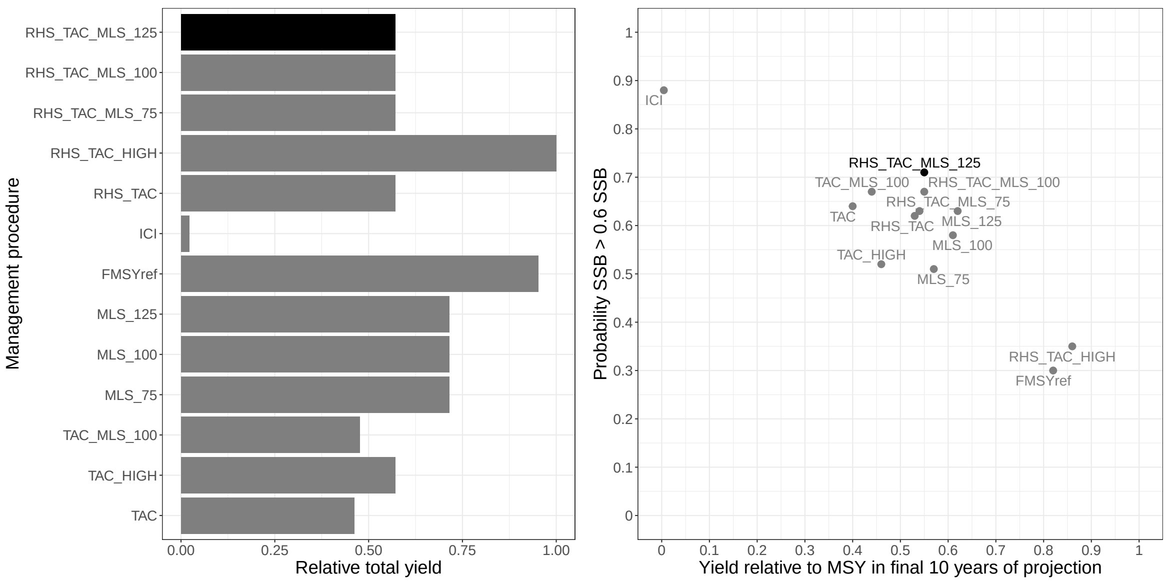

Figure 3.26: Brown sandfish trade off between biomass and yield relative to MSY

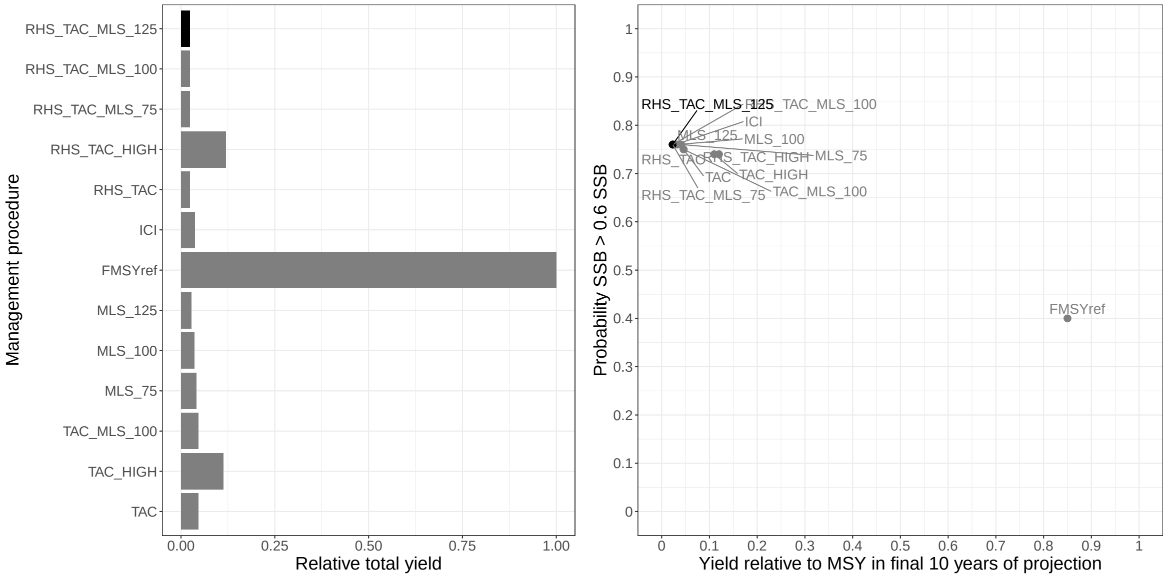

Figure 3.27: Hermanni curryfish trade off between biomass and yield relative to MSY

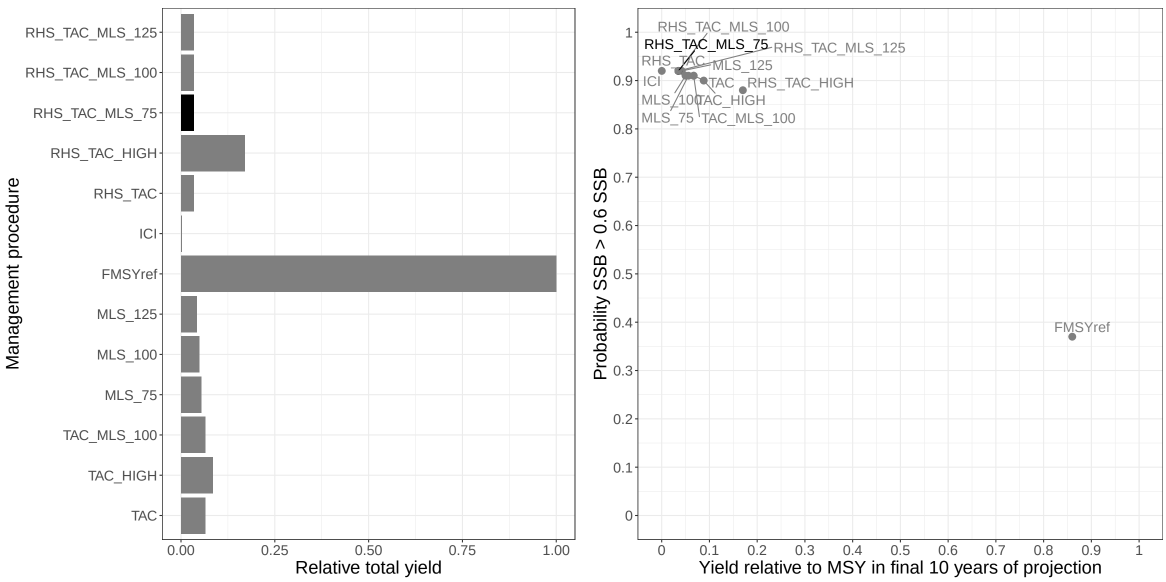

Figure 3.28: Golden sandfish trade off between biomass and yield relative to MSY

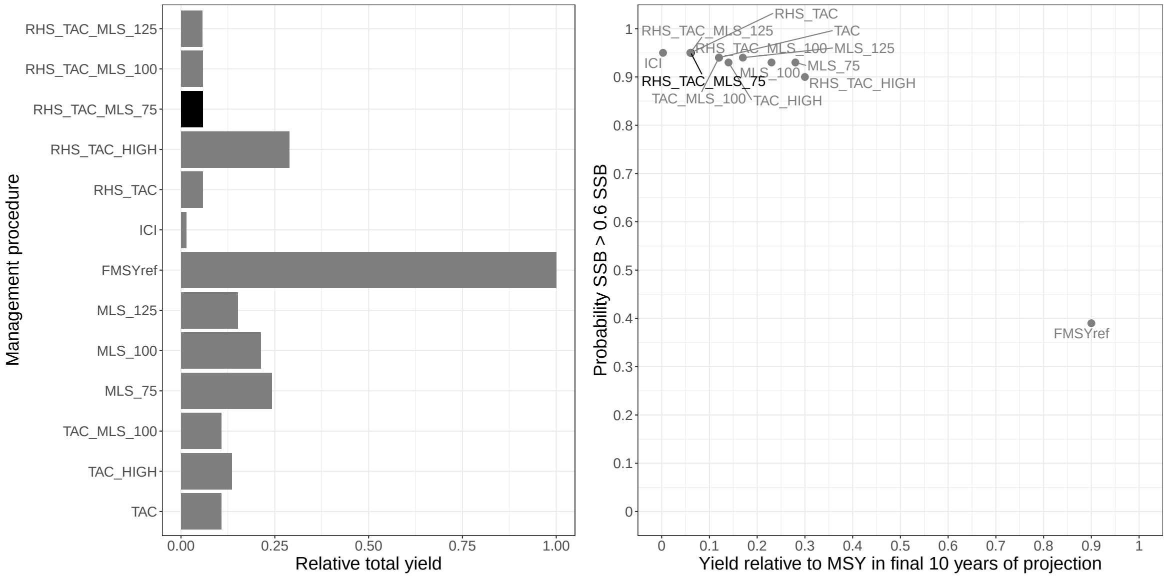

Figure 3.29: Leopardfish trade off between biomass and yield relative to MSY

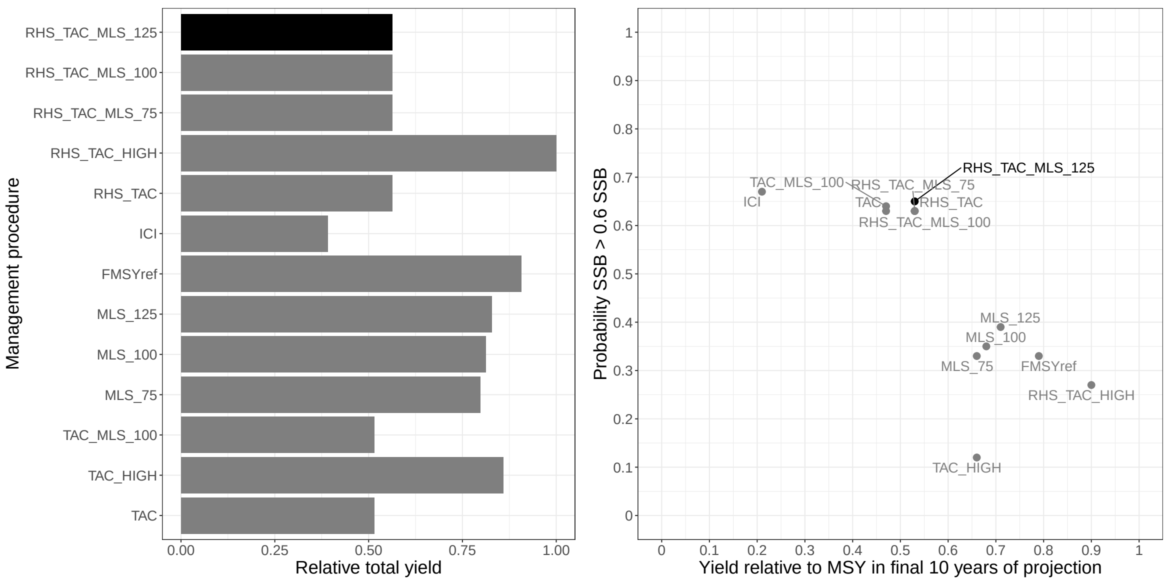

Figure 3.30: Sandfish trade off between biomass and yield relative to MSY

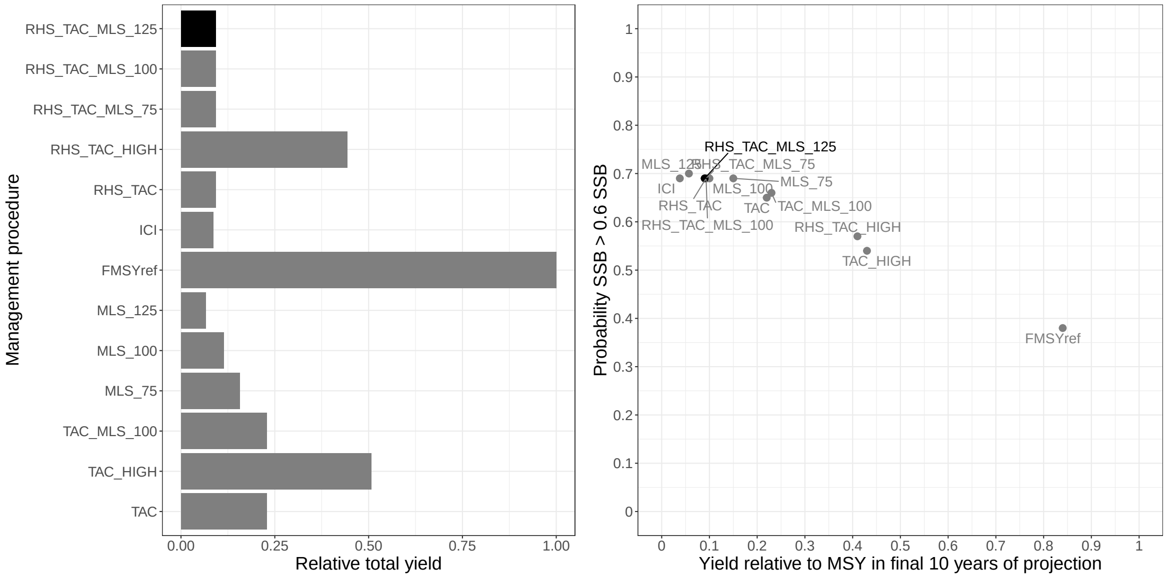

Figure 3.31: Vastus curryfish trade off between biomass and yield relative to MSY

3.3 Relative contribution of management approaches

Several MPs were applied to the fishery which include a combination of different management approaches such as TACs, size limits and spatial closures. Here, these management aspects and their relative contributions to fishery performance are considered, rather than specific MPs.

3.3.1 Total allowable catch

The TAC MP performed well for most species. All species, except white teatfish and blackfish, had over 50% of the simulations exceed the target biomass proportion of 60% (see Figure 3.15) and all species had over 80% of the simulations exceed the limit biomass proportion of 20% (see Figure 3.16). The median white teatfish and blackfish biomass trajectories approached 50% and 65% relative biomass, respectively. Seemingly, the poor performance is a result of uncertainty as the median results are favourable.

The TAC_HIGH MP pushed the limits of TAC management by tripling the catch from the last 10 years of the historical simulation. This resulted in the worst performing MP and highlighted the vulnerability of some species. In particular, black teatfish, blackfish, sandfish and white teatfish had less than 80% of the simulations exceed the limit biomass proportion of 20% (see Figure 3.16).

From these results, it is likely that there is a low risk to future overfishing when the TAC is set to reflect the catch from the past 10 years. This result is driven by conservative catches occurring within this period, that were likely reflective of the recent depletion of black teatfish in the late 1990's. Sea cucumber populations can decline quickly when catches are too high which makes setting a TAC on average catches difficult. However, the conservative nature of QSCF catches has not created this situation and resulting TACs set based on average catch have been appropriate. Here the TAC_HIGH MP demonstrated a situation where inflated catches cause demonstrable stock decline. Accordingly, the average catch TAC approach applied in the fishery has been effective and yields a low risk to overfishing. This is not a recommendation that other sea cucumber fisheries should follow, but rather a reflection on the cautious approach this fishery has taken to after a closure to the main species following an expansion that was too rapid.

The species most likely, in relative terms, to experience stock decline under current catch limits are black teatfish and white teatfish. This is due to their higher levels of exploitation placing their simulated biomass in 2023 at approximately 60% of unfished biomass. Accordingly, TACs set on average catch maintain a reasonable probability that their populations may be reduced below B_{60}. However, there was very little probability that their biomass's would approach B_{20}, indicating current catch levels would maintain current stock levels, rather than producing stock declines.

3.3.2 Minimum legal size

There are MLS restrictions in the QSCF which aim to allow individuals to breed once before being fished (McShane et al. 2022; Fisheries Queensland 2021). Size limits are notoriously difficult to implement in a sea cucumber fishery because the animals grow and shrink and some disintegrate when removed from water. Nevertheless, MLS protect the reproductive cycle of a population and are implemented in most Queensland fisheries.

The MLS_75, MLS_100 and MLS_125 MPs set size limits relative to the length-at-maturity with no restriction on catch. The relative biomass in the projection years was highest for MLS_125 and lowest for MLS_75 for all species. The larger MLS results in a higher relative biomass for two reasons: the amount of biomass vulnerable to fishing is reduced and more mature animals contribute to recruitment.

This is demonstrated in further detail in Figure 3.32 where a range of different MLS values are plotted against the percentage of simulations achieving the biomass targets for prickly redfish. Prickly redfish was chosen for the analysis since growth and maturity parameters were available in Conand (1989). The asymptotic length for the von Bertalanffy growth model was 66.3cm and the length at 50% and 95% maturity were 30 cm and 45 cm respectively. The current minimum legal size of 50 cm is therefore a conservative limit to ensure animals spawn before becoming available to the fishery.

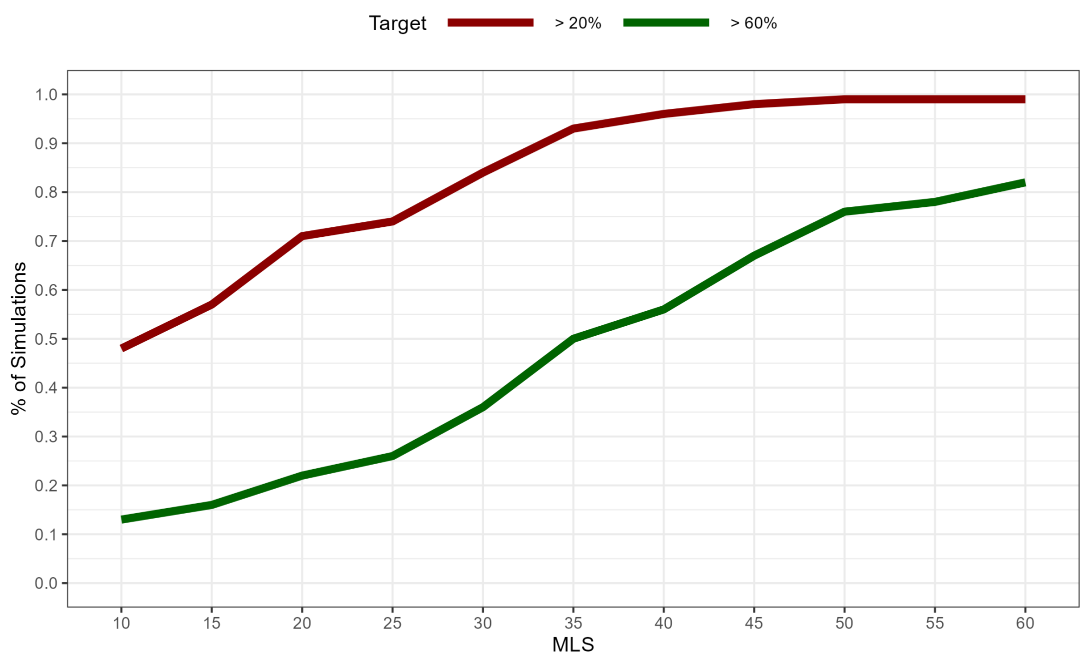

Figure 3.32: The percentage of simulations that exceed the target and limit biomass levels for increasing MLS management

The prickly redfish operating model was subjected to an extreme MP with a TAC 100 times greater than the catch from the past 10 years. Figure 3.32 shows that approximately all of the simulations across all the projection years have a biomass above 20% of virgin biomass at the current minimum legal size of 50 cm. As the MLS decreases and more of the biomass becomes available to fishing, these statistics decline such that when the MLS is 10 cm only 13% of simulations remain above 60% of spawning stock biomass.

This context is important to consider, as the results show that the implementation of a large MLS relative to length-at-maturity improves MP performance. However, differences in long term yield are often only marginal or sometimes higher for larger MLS. Therefore, while rotational harvest will reduce localised depletion and appropriate TACs help avoid excessive harvest, these results demonstrate that an appropriate MLS is the most effective management measure that can be implemented in the fishery. Once an appropriate MLS has been implemented for a species, further management measures would further improve fishery performance from a strong management baseline.

3.3.3 Rotational harvest strategy

The RHS MPs performed similarly to, and in most cases exceeded the performance of, the corresponding non-spatial MPs (Figure 3.15). The $B > B_{60}$ PM examines the proportion of simulations that cross B_{60} rather than the degree to which these simulations may extend below B_{60}. For some species, this PM showed a slightly greater proportion of simulations remaining above this reference point (i.e., white teatfish) (Figure 3.15). However, the corresponding biomass projections often showed a higher median biomass trajectory was achieved for the RHS MPs in comparison to the corresponding non-spatial MPs (Figures C.35 and C.36). This holistic examination of results indicates that the RHS MPs performed best across species but had greater variation between simulations, as would be expected given the added complexity of spatial structure. The RHS MPs also provided the best balance between sustainability ($B > B_{60}$) versus yield, whereby larger biomass's were maintained leading to larger catches across the projection period (Figure 3.18).

3.3.4 Catch rate and effort

Two MPs from *openMSE* were also applied to explore types of management novel to QSCF and provoke informative comparisons. ICI, or 'Index Confidence Interval', is a TAC-based MP that adjusts the TAC according to the catch rate index. If the index is below the lower bound of the confidence interval of mean historical index, the TAC is reduced by 25%. If the index is above the upper bound of the confidence interval of mean historical index, the TAC is increased by 5%. This MP relies completely on catch rates to accurately inform the abundance of the species. ICI will likely consequently fail for species that exhibit hyperstable or hyperdepleted catch rates. Recent stock assessments suggest this is the case for sea cucumber species (Smart et al. 2024a; Smart et al. 2024b). For most species, the ICI approach resulted in a closed fishery due to over-cautious reductions in TAC despite a very high biomass but showed some promise for black teatfish, sandfish and white teatfish. These three species have lower relative biomass, likely contributing to more informative catch rates. ICI may be appropriate for depleted stocks if the goal is to maintain a safe level of catch.

FMSYref is an effort-based MP provided by *openMSE* that aims to recommend an effort that achieves F_{MSY} when paired with the historical catchability value. F_{MSY} is an internal value of the operating model simulations and is not known in reality. The MP is therefore not a realistic management tool but allows for intuitive metrics of yield and exploitation. F_{MSY} led to catches that were too high and increased the risk of overfishing for numerous species.

3.3.5 GBRMP protected areas

In 2004, the RAP introduced a series of closed areas to the GBR which protected a substantial amount of sea cucumber habitat. Two types of zones provide protections to sea cucumber populations: green and yellow zones, where the QSCF cannot fish. For simplicity, these zones are labelled 'Green zone' in figures but include yellow zones as well. These closures were specified in the OMs to include 37% of the the sea cucumber populations since their implementation in 2004 given that this is the area of the GBR which they cover.

For some species, the green zone and fishery trajectories show varying degrees of divergence in the historical period due to differences in the specification of spatial components. For example, the white teatfish operating models show a clear separation between the relative biomass of green zones and fishery areas. The RAP closed green zones from fishing in the same year the TAC for white teatfish was increased, shifting a lot of effort to the fishery areas where depletion is greater. On the other hand, the black teatfish operating models specified a stock with heavy fishing for 10 years before the closure of BTF in October of 1999 and the subsequent implementation of green zones in 2004 so Figure 3.1 shows consistency between the green zone and the fishery for the historical period. For the Bunker and Gould operating models, the green zone is sufficiently mixed (through recruitment) with the fishery area leading to identical trajectories for the green zone and the fishery. Tier 2 species exhibit the same variation in the historical period.

Given a global stock recruitment relationship is used in *openMSE*, the populations within these zones are reproductively linked to populations from the fished areas. These zones therefore provide some recruitment to fished areas while also receiving some recruitment reciprocally. This specifies an OM where the benefit of MPAs is provided to all MPs. However, the populations within the MPA can also be affected by population declines in the fished areas. A good example of this dynamic can be seen in the biomass projection for the TAC_HIGH MP for white teatfish (Figure C.35). Here, elevated catches substantially decreased the biomass in the fished area and caused a corresponding decrease in the green zone, albeit at a much slower rate. The presence of a green zone provided some recruitment to the fished area, slowing its biomass decline despite these high catches. For other MPs that allowed white teatfish biomass to increase in fished areas, a similar increase occurred in the green zone (Figure C.35). This demonstrates that the GBRMP is providing substantial benefit to these populations, in addition to the dedicated management in place for this fishery.

4 Discussion

4.1 Fishery performance

Fisheries management can have multiple objectives that are often conflicting. For example, increasing yield and biomass simultaneously is rarely possible as increased catches will intuitively decrease the population. Therefore, the results of an MSE can be highly faceted with final recommendations often representing suitable trade-offs between objectives. This is even more the case in multi-species fisheries with identical (or at least similar) management applied across species who may respond differently to it. However, the results of this MSE indicate that for the QSCF a reasonably consistent set of conclusions can be drawn across species, simplifying the implementation of the recommendations.

The best overall MP for the QSCF (except burrowing blackfish in the BBZs) was the RHS_TAC_MLS_125 MP. This is the MP currently applied to most species in the fishery with the exception of burrowing blackfish managed in the BBZs, and black teatfish, leopardfish, golden sandfish and blackfish whose MLS is at or below length-at-maturity. After dismissing MPs that created a high risk to sustainability, the RHS_TAC_MLS_125 MP provided one of the highest long term yields for all species. While similar MPs with a lower MLS (RHS_TAC_MLS_75 and RHS_TAC_MLS_100) produced higher yields for some species, this was often marginal and had a trade off with slightly higher risks to sustainability. There was no species where the RHS_TAC_MLS_125 MP produced an unsatisfactory yield and in most cases it had the lowest risk to sustainability while achieving this. For burrowing blackfish stocks that are not managed via the RHS, most of the MPs performed similarly as both the Bunker and Gould stocks were recently estimated to be at high levels and this was represented in their OMs (Smart et al. 2024a). Therefore, recent levels of catch and any reasonable increases through a TAC tended to result in low risks to overfishing.

The RHS_TAC_MLS_125 MP used a TAC based on average catch over the last ten historical years, the RHS and an MLS set 25% above length-at-maturity. This trifecta of management was successful as each component added complementary value to the fishery's management. A TAC rather than an effort based value is more appropriate for multi-species dive fisheries as they have strong selectivity. Therefore, accounting for high levels of species targeting is difficult to incorporate within effort limits which would be aggregated across species and can be manipulated to increase fishing pressure on certain stocks. Individual catch limits, set at appropriate levels, are often a better mechanism of maintaining individual species sustainability in these fisheries as effort is appropriately spread across species. The implementation of the RHS further spreads this effort spatially, avoiding localised population depletion. For some species, such as sandfish, MPs that included the RHS performed notably better than non-spatial MPs. There was no occasion where the RHS performed measurably worse than a non-spatial MP for any species when yield and risk to overfishing were simultaneously considered. Lastly, and most importantly, an MLS above length-at-maturity provides substantial resilience to overfishing as more individuals are able to reproduce prior to harvest. This is a well documented benefit of size limits, which is best described by the 'spawn-at-least-once' paradigm that states that stock collapse becomes impossible at any level of F so long as every spawner produces one replacement spawner prior to harvest (Myers et al. 1998). The large MLS for several species therefore ensures the population's reproductive output is increased prior to harvest. Across MPs, a larger MLS tended to reduce the risk to overfishing unless that risk was already small from other MPs with low TACs.

The most valuable species in the fishery, black teatfish and white teatfish, had the highest risk to sustainability, relatively speaking. These species have the longest catch histories which produced historical simulations where the median biomass was closer to 60% of unfished levels. Consequently, a higher number of simulations remained below this B_{60} reference point in comparison to other species whose median biomass was above this level at the end of the historical period. While the number of simulations where $B < B_{60}$ was relatively higher, this did not represent a poorer performance of MPS but rather a different starting point at the beginning of the projection period. Uncertainty in their current relative biomass levels stem from uncertainty in recent assessments where black teatfish has an anecdotal stock collapse predating current fishing records and white teatfish does not yet have biomass estimated from a survey (Helidoniotis 2021a; Helidoniotis 2021b). Future stock assessments that reduce this uncertainty may be worth reconsidering within an MSE as they will likely remove uncertainty from the respective OMs and provide more valuable management recommendations.

4.2 Context of this MSE

A previous MSE was undertaken for the QSCF by Skewes et al. (2014) which has many similarities to the MSE presented in this report. The goal of the previous MSE was to provide an initial assessment of the RHS which had been implemented eight years prior through a common sense approach designed by industry. However, at the time this had not been scientifically tested. Similarities between this MSE and that of Skewes et al. (2014) included the MPs considered (a mixture of catch limits, size limits and the RHS), the model structure (age structured) and very similar data on fishing dynamics and biological information. In many ways, the present MSE is an update to Skewes et al. (2014) which incorporated a longer time series (1995–2023 versus 1995–2012), a larger number of species (twelve versus nine) and was capable of undertaking a greater number of simulations given computational advancements (100 simulations per MP rather than ten per MP). A key, but important, difference between the two MSEs was that Skewes et al. (2014) applied local stock recruitment dynamics to simulate isolated populations in each fishing zone, while this MSE applied a global stock recruitment relationship that shared recruitment across areas. The Skewes et al. (2014) MSE therefore tested the efficacy of the RHS by considering self-seeding populations with no movement nor spillover of recruitment, while the present MSE did the opposite. The current MSE therefore has a greater ability to consider the contribution of closed areas, such as green zones and closed rotational zones, to the populations that are open to fishing. While some specific results differ between the MSEs, and are difficult to compare as fishery reference points have been updated between reports (Fisheries Queensland 2021), consistent conclusions were still reached. These include:

- The RHS reduces the risk of localised depletion, decreases the risk to broader overfishing and improves long term fishery yield.
- Size limits are important in the fishery and more information is required on length-at-maturity to inform these limits for various species.
- Species such as prickly redfish had the lowest risk to depletion through the RHS while species that have had larger historical harvests such as black teatfish and white teatfish had the largest risk. However, this risk was still deemed appropriately low.

The present MSE should therefore be considered complementary to the previous work by Skewes et al. (2014) and it would be reasonable to consider management recommendations from both reports.

Two independent MSEs being undertaken on the same fishery within ten years of one another is fairly irregular and was prompted by several reasons. Firstly, four species in the fishery have been listed on CITES Appendix II prompting non-detriment requirements for fishery exports to continue. Secondly, given the depletion of sandfish and black teatfish in the late 1990's, much of the fishery's evolution has occurred through a cautious level of industry self management that aimed to avoid further population declines. For an extended period, this evolution occurred with little scientific basis as biological information and stock assessments were missing for many species. This shortcoming has (not unreasonably) been highlighted in the literature (Eriksson et al. 2015; Purcell et al. 2015; Wolfe et al. 2022) but has now been addressed through the application of two MSEs (Skewes et al. 2014), stock assessments for tier 1 and important tier 2 species (Helidoniotis 2021a; Helidoniotis 2021b; Smart et al. 2024a; Smart et al. 2024b), provision of species biological information (McSpadden et al. in review, Williamson et al. in prep) and estimation of absolute biomass through scientific surveys (Knuckey et al. 2016; Koopman et al. 2019; Knuckey et al. 2021; Koopman et al. 2022; Koopman et al. 2023; Koopman et al. 2024a).

Many sea cucumber fisheries have had a boom and bust history and have declined as quickly as they have expanded (Anderson et al. 2011; Purcell et al. 2013). This occurs through serial overexploitation where the most economically viable populations are initially fished with effort shifting to new areas, size classes and eventually species as overexploitation occurs (Anderson et al. 2011). This boom and bust nature of sea cucumber fisheries has been described as very predictable (Anderson et al. 2011) and it is easy to see why strong conservation focus has occurred for the QSCF givens its initial stock declines in late 1990s. However, an important difference exists between the QSCF and the archetypal boom and bust sea cucumber fishery which is the proactive and precautionary management implemented since the early 2000's. Recognition of the potential for rapid sea cucumber population declines and action taken by industry and fisheries management to address this have steered the fishery in a different direction. Between 2004 and 2023 numerous management measures have been implemented that include the GBRMP RAP, the RHS, catch limits (TACs and catch triggers) and minimum size limits. Most of these management measures are particularly cautious given that the RHS is the most extensive spatial management arrangement implemented for a sea cucumber fishery and the size limits for most species are larger than (or at least equal to) corresponding species limits from similar fisheries (McShane et al. 2022). Therefore, while there are similarities between the QSCF any other sea cucumber fisheries that have unfortunately been overexploited, there are also key differences that have led to its successful management. While the transparency of this may have been missing previously (Eriksson et al. 2015; Wolfe et al. 2022), this MSE along with other research conducted over the past ten years provides greater clarity over the status of the fishery and the effectiveness if its management. However, calls for greater research into species biology remain justified (Skewes et al. 2014; Eriksson et al. 2015; Purcell et al. 2015; Wolfe et al. 2022).

Results from the MSE conducted by Skewes et al. (2014) were presented in a global context by Plagányi et al. (2015) who highlighted value of relatively low-cost, low-information and comanaged rotational harvest approaches for other fisheries. While the RHS of the QSCF serves as an important example of how a sea cucumber fishery can be fished sustainably, there are aspects of this approach that make it difficult to apply broadly to a number of other tropical fisheries. Governance is the main issue with many tropical fisheries in developing nations having open-access, and weak technical and enforcement capacity (Purcell et al. 2015). Therefore, while the results of this MSE and that of Skewes et al. (2014) highlight the success of the RHS for the QSCF, its wider application to similar fisheries may not be possible.

4.3 Limitations/Unmodelled influences

4.3.1 Modelling limitations

There are three areas of modelling limitations within this MSE that should be discussed. The first is the failed application of closed-loop MPs attempted for the recently assessed species: burrowing blackfish, prickly redfish, vastus curryfish and herrmanni curryfish. The stock assessments for these stocks were reliant on estimates of absolute biomass available from recent surveys (Smart et al. 2024a; Smart et al. 2024b). These were necessary for reliable model outputs to be produced given the data-limited nature of the fishery. However, a single estimate of absolute biomass can overcome a reasonable degree of data limitations. This estimate provides an anchoring point that a stock assessment can use to determine a depletion history from catch and effort information. However, the in-built assessment models from *openMSE* do not allow such surveys to be specified. These models instead rely on catch and effort information and cannot consider the recent QSCF surveys within an MSE context. It was not surprising that these in-built models would be implemented unsuccessfully for these OMs (Appendix D). Therefore, the MPs were dismissed and not presented as part of the MSE outputs. In reality, ongoing surveys and stock assessments would benefit the fishery and their consideration within a management framework would be valuable. Future MSE work would benefit from incorporating these models into an MSE, although this may be difficult to achieve using the *openMSE* framework.

The second limitation is the use of a global stock recruitment relationship for a highly spatial fishery. Although the RHS MPs enabled uneven distribution of fishing effort and therefore a higher risk of localised depletion, the global stock recruitment relationship likely blurs the effects of compounding reductions in recruitment. Many sea cucumber species are considered to have genetic connectivity over a large area with a meta-population structure. Therefore, while these may form a singular large genetic population, they may operate as a series of interconnected sub populations with some degree of self-seeding (Skewes 2023). This is a complicated stock structure to incorporate into an MSE and future work may consider local stock recruitment relationships. However, the scale of self-seeding is unknown for many populations and it is possible that this occurs across multiple adjacent zones that are open or closed to fishing. Therefore, it is conceivable that closed areas assist with repopulating fished areas, swaying the stock structure towards a global stock recruitment relationship. Determining the exact population structure for every species in the fishery is a difficult task. However, the consideration and comparison of different stock recruitment dynamics in an MSE would be valuable and could further demonstrate that the RHS minimises the risk of localised depletion. A previous MSE conducted by Skewes et al. (2014) used a local stock recruitment relationship for each OM zone. This MSE also demonstrated the effectiveness of the RHS in avoiding localised depletion (Skewes et al. 2014), providing evidence that applying a global or local stock recruitment relationship leads to the same MSE outcomes. A natural extension of the Skewes et al. (2014) and the present MSE would be to fully account for a meta-population structure stock recruitment dynamics. However, this is not a trivial undertaking and would require substantial model development. In the mean time, the independent application of two distinct stock recruitment assumptions yielding the same results provides confidence that the RHS has been successful.

The third limitation regards the omission of the Lizard burrowing blackfish stock from this MSE. There are three burrowing blackfish zones (BBZ) that are treated as distinct management units in the QSCF (Fisheries Queensland 2021). Recent evidence has suggested a large stock decline of burrowing blackfish has occurred in the Lizard BBZ that is environmentally driven (Smart et al. 2024a; Koopman et al. 2024b). Three biomass surveys have tracked this decline (Leeworthy 2007; Koopman et al. 2022; Koopman et al. 2024b) which has occurred at a rate faster than can be described through the fishing.

The recent burrowing blackfish stock assessment report identified this issue and highlighted the need for tailored population modelling to capture these environmentally driven population dynamics. It was not possible to appropriately include this stock in this MSE without that information. However, even with strong insight into the dynamics of this stock, it remains unlikely that an MSE would provide any management recommendations beyond a zone closure. The environmentally driven decline of the Lizard stock highlights the possibility of similar impacts to other sea cucumber stocks. However, depletion caused or accelerated by influences other than fishing were not explored in this report. Environmental effects can be effectively explored in an MSE framework such as Blamey et al. (2021) which successfully evaluated harvest control rules of Australian prawn stocks subject to environmental variability.

The situation with regards to the Lizard Island population can be summarised as follows:

- Stock assessment population model parameters were not able to be satisfactorily estimated. This was primarily due to the fact that biomass surveys showed significant declines that couldn't be explained solely by fishing, to the extent that standard population modeling theory could not be directly applied.
- There was insufficient time to incorporate the Lizard BBZ in the MSE analysis due to the relatively late timing (in terms of the timelines for this MSE project) of biomass survey data. This data reinforced our understanding of this stock's population dynamics which, combined with the additional complexity involved in appropriately setting up an MSE for this type of population, meant that an appropriate OM could not be constructed within the available time frame.
- The Lizard BBZ is currently voluntarily closed to fishing.

4.3.2 Data limitations

The biology of many sea cucumber species is unknown or uncertain and often places this taxon in a data-limited space. This can be problematic for many fisheries whose development often outpaces the rate of science for a species (Friedman et al. 2011). This applies to many species in the QSCF and has been explicitly structured into this MSE through an increased level of uncertainty for species biology which is presented in Appendix A. A consequence of this is that more uncertainty occurs within the MSE although this has not impacted the results which are able to confidently provide recommendations despite species knowledge gaps.

A principal conclusion of this MSE is the importance of size limits for species in the QSCF and setting an MLS that is cautiously above length-at-maturity. Without accurate maturity data the MSE is still able to assess the efficacy of these size limits and provide management recommendations. However, the implementation of these recommendations requires appropriate data to be collected. Robust estimates of maturity are lacking for many species within this assessment (Appendix A) and therefore this information must be attained in order for this management recommendation to be successfully implemented across the QSCF. From the maturity information available for some species, there is a consistent result of maturity occurring at 40–50% of maximum length (Conand 1989), which is generally well known for most of these species. The next step in implementing appropriate size limits is to attain robust maturity information for all of the species and reconsider their MLS where appropriate.

4.4 Recommendations

This MSE has incorporated a larger level of uncertainty than is often typical, as biological information is sparse for tropical sea cucumbers. Therefore, research into species biology, particularly maturity, is an important recommendation of this report. Species particularly in need of information include vastus curryfish who is missing information on growth and maturity, and black teatfish, white teatfish, burrowing blackfish and herrmanni curryfish who are missing information on growth. These species constitute the majority of the QSCF catch and are the tier 1 and important tier 2 species in the fishery, along with prickly redfish who is well studied by comparison (Conand 1989). Biological research is required for remaining species in the fishery but is less urgent while their exploitation remains low.

The conservative TACs and catch triggers that are implemented do not pose a risk to sustainability. where alternative TACs (set at 3 times the average catch) where applied in this MSE, a relatively higher risk to overfishing occurred to some species. Therefore, future catch increases should be considered carefully and should refer to the results of this MSE and any corresponding stock assessments.

This MSE demonstrated that an MLS should be set 25% above length-at-maturity to gain the lowest risk to sustainability. This has been applied for some species while others have a smaller MLS or are missing maturity information. Setting a conservative MLS for each species demonstrably reduces the risk to sustainability regardless of other management considerations. The QSCF has already implemented some of the most conservative MLS relative to other fisheries (McShane et al. 2022). The extension of this to the remaining species in the fishery is recommended.

4.5 Conclusion

This report undertook an MSE on the QSCF, a multi-species, highly spatial fishery operating within the GBRMP. The analysis was undertaken using the *openMSE* platform and OMs for each species were built using the best available information. Where information was unavailable or uncertain, additional uncertainty was simulated through the analysis to ensure no bias was introduced to the analyses. Several MPs were applied to twelve species that considered a diversity of approaches such as catch limits, size limits, effort based controls and spatial management. Many of these MPs applied a combination of these management approaches as is representative of the fishery's diverse array of management.

The MSE found the settings contained in the 'Queensland Sea cucumber fishery harvest strategy 2021-2026' and other legislated and enforceable management arrangements are likely sufficient to meet the fishery's objective of attaining maximum economic yield (defined in the harvest strategy as target biomass level of 60% of unfished biomass for stocks harvested in the fishery). The current management containing the rotational harvest strategy, catch limits and size limits suggests the risk of depletion for most species was low. Results indicated some risk to species with a history of high catch such as black teatfish, white teatfish and sandfish if similar catches were reinstated.

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Appendix A Operating model parameters

Table A.1: Descriptions of the operating model parameters

Parameter	Description
A_{max}	plus group (age where $< 1\%$ of population survives)
M	natural mortality
L_{∞}	asymptotic length
κ	growth coefficient
t_0	growth coefficient
L_{50}	length at 50% maturity
L_{50-95}	length difference between 50% and 95% maturity
a	weight-length parameter
b	weight-length parameter
D	depletion
R_0	virgin recruitment

Table A.2: The parameters used to define the stock object for each species and where the values were sourced from

Species	Parameter	Value	Source
Amberfish	A_{max}	16	Approximated based on biological understanding. Additional uncertainty added
	M	0.3 – 0.7	Approximated based on biological understanding. Additional uncertainty added
	L_{∞}	70 – 80	Approximated based on biological understanding. Additional uncertainty added
	κ	0.2 – 0.35	Approximated based on biological understanding. Additional uncertainty added
	t_0	0	Approximated based on biological understanding. Additional uncertainty added
	L_{50}	28 – 38	Approximated based on biological understanding. Additional uncertainty added
	L_{50-95}	5 – 20	Approximated based on biological understanding. Additional uncertainty added
	a	0.000092	Conand (1989)
	b	2.65	Conand (1989)

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Table A.2 – *Continued from previous page*

Species	Parameter	Value	Source
	D	0.2 – 1	No stock assessment available. Wide range used
	R_0	1000	Tuned so that historical catches approximate actual catch
Blackfish	A_{max}	14	Approximated based on biological understanding. Additional uncertainty added
	M	0.5 – 0.8	Approximated based on biological understanding. Additional uncertainty added
	L_∞	30 – 40	Approximated based on biological understanding. Additional uncertainty added
	κ	0.2 – 0.35	Approximated based on biological understanding. Additional uncertainty added
	t_0	0	Approximated based on biological understanding. Additional uncertainty added
	L_{50}	12 – 18	Approximated based on biological understanding. Additional uncertainty added
	L_{50-95}	3 – 8	Approximated based on biological understanding. Additional uncertainty added
	a	0.0013	Estimate for burrowing blackfish (similar species) from Koopman et al. (2019)
	b	1.949	Estimate for burrowing blackfish (similar species) from Koopman et al. (2019)
	D	0.2 – 1	No stock assessment available. Wide range used
	R_0	2000	Tuned so that historical catches approximate actual catch
Brown sandfish	A_{max}	14	Approximated based on biological understanding. Additional uncertainty added
	M	0.5 – 0.8	Approximated based on biological understanding. Additional uncertainty added
	L_∞	30 – 45	Approximated based on biological understanding. Additional uncertainty added
	κ	0.4 – 0.6	Approximated based on biological understanding. Additional uncertainty added
	t_0	0	Approximated based on biological understanding. Additional uncertainty added
	L_{50}	12 – 18	Approximated based on biological understanding. Additional uncertainty added
	L_{50-95}	5 – 8	Approximated based on biological understanding. Additional uncertainty added
	a	0.001974	Approximated based on biological understanding. Additional uncertainty added

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Table A.2 – *Continued from previous page*

Species	Parameter	Value	Source
	b	1.83	Approximated based on biological understanding. Additional uncertainty added
	D	0.2 – 1	No stock assessment available. Wide range used
	R_0	500	Tuned so that historical catches approximate actual catch
Black teatfish	A_{max}	14	Approximated based on biological understanding. Additional uncertainty added
	M	0.3 – 0.6	Approximated based on biological understanding. Additional uncertainty added
	L_{∞}	50 – 58	Approximated based on biological understanding. Additional uncertainty added
	κ	0.2 – 0.35	Approximated based on biological understanding. Additional uncertainty added
	t_0	0	Approximated based on biological understanding. Additional uncertainty added
	L_{50}	20 – 30	Conand (1989)
	L_{50-95}	5 – 15	Conand (1989)
	a	0.0003	Conand (1989)
	b	2.55	Conand (1989)
	D	0.2 – 0.6	Approximated based on exploitation history
	R_0	1000	Tuned so that historical catches approximate actual catch
Golden sandfish	A_{max}	14	Approximated based on biological understanding. Additional uncertainty added
	M	0.5 – 0.8	Approximated based on biological understanding. Additional uncertainty added
	L_{∞}	40 – 50	Approximated based on biological understanding. Additional uncertainty added
	κ	0.4 – 0.6	Approximated based on biological understanding. Additional uncertainty added
	t_0	0	Approximated based on biological understanding. Additional uncertainty added
	L_{50}	18 – 25	Conand (1989)
	L_{50-95}	5 – 8	Conand (1989)
	a	0.0005	Conand (1989)
	b	2.26	Conand (1989)
	D	0.2 – 1	No stock assessment available. Wide range used
	R_0	1000	Tuned so that historical catches approximate actual catch

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Table A.2 – *Continued from previous page*

Species	Parameter	Value	Source
Herrmanni curry-fish	A_{max}	20	Approximated based on biological understanding. Additional uncertainty added
	M	0.3 – 0.7	Approximated based on biological understanding. Additional uncertainty added
	L_{∞}	50 – 60	Approximated based on biological understanding. Additional uncertainty added
	κ	0.2 – 0.35	Approximated based on biological understanding. Additional uncertainty added
	t_0	0	Approximated based on biological understanding. Additional uncertainty added
	L_{50}	23 – 30	Conand (1993)
	L_{50-95}	5 – 10	Approximated based on biological understanding. Additional uncertainty added
	a	0.019	Koopman et al. (2024a)
	b	1.408	Koopman et al. (2024a)
	D	0.79 – 1	95% credible interval from stock assessment result
	R_0	11655	MLE estimate from stock assessment result
Leopardfish	A_{max}	16	Approximated based on biological understanding. Additional uncertainty added
	M	0.3 – 0.5	Approximated based on biological understanding. Additional uncertainty added
	L_{∞}	40 – 60	Approximated based on biological understanding. Additional uncertainty added
	κ	0.2 – 0.4	Approximated based on biological understanding. Additional uncertainty added
	t_0	0	Approximated based on biological understanding. Additional uncertainty added
	L_{50}	20 – 35	Approximated based on biological understanding. Additional uncertainty added
	L_{50-95}	5 – 15	Approximated based on biological understanding. Additional uncertainty added
	a	0.001974	Approximated based on biological understanding. Additional uncertainty added
	b	0.83	Approximated based on biological understanding. Additional uncertainty added
	D	0.2 – 1	No stock assessment available. Wide range used
	R_0	1000	Tuned so that historical catches approximate actual catch
Prickly redfish	A_{max}	16	Approximated based on von Bertalanffy growth
	M	0.3 – 0.7	Conand (1989)

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Table A.2 – *Continued from previous page*

Species	Parameter	Value	Source
	L_∞	60 – 70	Conand (1989)
	κ	0.2 – 0.35	Conand (1989)
	t_0	0	Conand (1989)
	L_{50}	28 – 38	Conand (1989)
	L_{50-95}	5 – 20	Approximated based on biological understanding. Additional uncertainty added
	a	0.055	Koopman et al. (2024a)
	b	1.154	Koopman et al. (2024a)
	D	0.7 – 1	95% credible interval from stock assessment result.
	R_0	10521.9	MLE estimate from stock assessment result.
Sandfish	A_{max}	14	Approximated based on biological understanding. Additional uncertainty added
	M	0.3 – 0.7	Approximated based on biological understanding. Additional uncertainty added
	L_∞	35 – 50	Approximated based on biological understanding. Additional uncertainty added
	κ	0.4 – 0.6	Approximated based on biological understanding. Additional uncertainty added
	t_0	0	Approximated based on biological understanding. Additional uncertainty added
	L_{50}	10 – 15	Conand (1989)
	L_{50-95}	5 – 8	Conand (1989)
	a	0.0001974	Conand (1989)
	b	1.83	Conand (1989)
	D	0.2 – 1	No stock assessment available. Wide range used
	R_0	1000	Tuned so that historical catches approximate actual catch
Vastus curryfish	A_{max}	16	Approximated based on biological understanding. Additional uncertainty added
	M	0.3 – 0.7	Approximated based on biological understanding. Additional uncertainty added
	L_∞	35 – 45	Approximated based on biological understanding. Additional uncertainty added
	κ	0.2 – 0.35	Approximated based on biological understanding. Additional uncertainty added
	t_0	0	Approximated based on biological understanding. Additional uncertainty added
	L_{50}	20 – 30	Approximated based on herrmanni curryfish maturity.

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Table A.2 – *Continued from previous page*

Species	Parameter	Value	Source
	L_{50-95}	5 – 10	Approximated based on herrmanni curryfish maturity.
	a	0.019	Approximated based on herrmanni curryfish.
	b	1.408	Approximated based on herrmanni curryfish.
	D	0.6 – 1	95% credible interval from stock assessment result.
	R_0	16582.5	MLE estimate from stock assessment result
White teatfish	A_{max}	14	Approximated based on biological understanding. Additional uncertainty added
	M	0.3 – 0.6	Approximated based on biological understanding. Additional uncertainty added
	L_∞	50 – 58	Approximated based on biological understanding. Additional uncertainty added
	κ	0.2 – 0.35	Approximated based on biological understanding. Additional uncertainty added
	t_0	0	Approximated based on biological understanding. Additional uncertainty added
	L_{50}	25 – 35	Conand (1989)
	L_{50-95}	5 – 15	Conand (1989)
	a	0.00037	Conand (1989)
	b	2.34	Conand (1989)
	D	0.2 – 1	No biomass survey available. Wide range used
	R_0	1500	Tuned so that historical catches approximate actual catch
Burrowing blackfish	A_{max}	20	Approximated based on biological understanding. Additional uncertainty added
Bunker	M	0.3 – 0.8	Approximated based on biological understanding. Additional uncertainty added
	L_∞	35 – 45	Approximated based on biological understanding. Additional uncertainty added
	κ	0.2 – 0.35	Approximated based on biological understanding. Additional uncertainty added
	t_0	0	Approximated based on biological understanding. Additional uncertainty added
	L_{50}	15 – 25	Williamson et al. in prep
	L_{50-95}	5 – 10	Williamson et al. in prep
	a	0.001303112	Koopman et al. (2019)
	b	1.949	Koopman et al. (2019)
	D	0.8 – 1	95% credible interval from stock assessment result.
	R_0	14070.2	MLE estimate from stock assessment result

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Table A.2 – *Continued from previous page*

Species	Parameter	Value	Source
Burrowing blackfish Gould	A_{max}	20	Approximated based on biological understanding. Additional uncertainty added
	M	0.3 – 0.8	Approximated based on biological understanding. Additional uncertainty added
	L_{∞}	35 – 45	Approximated based on biological understanding. Additional uncertainty added
	κ	0.2 – 0.35	Approximated based on biological understanding. Additional uncertainty added
	t_0	0	Approximated based on biological understanding. Additional uncertainty added
	L_{50}	15 – 25	Williamson et al. in prep
	L_{50-95}	5 – 10	Williamson et al. in prep
	a	0.001303112	Koopman et al. (2019)
	b	1.949	Koopman et al. (2019)
	D	0.67 – 0.97	95% credible interval from stock assessment result.
	R_0	14311.1	MLE estimate from stock assessment result

Appendix B Life history

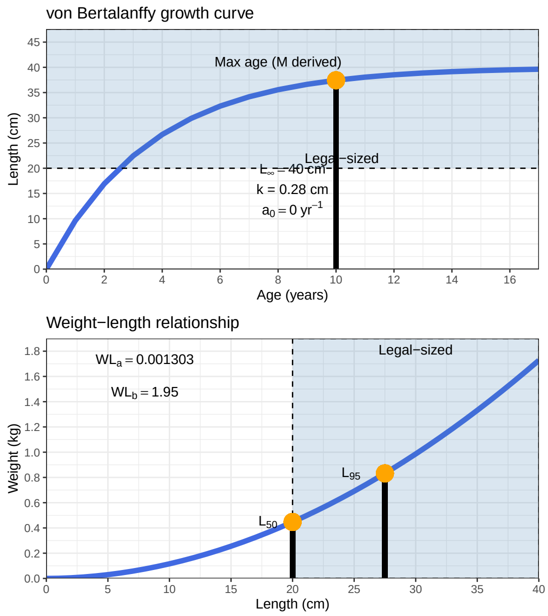

Figure B.1: Life history defined by mean parameters specified for the burrowing blackfish operating model

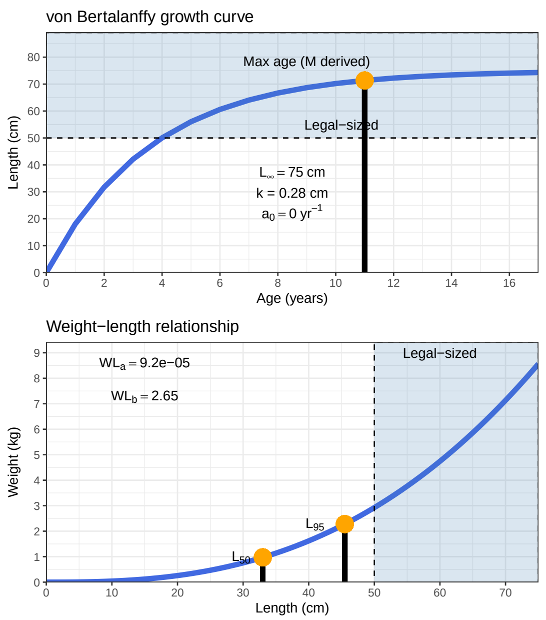

Figure B.2: Life history defined by mean parameters specified for the amberfish operating model

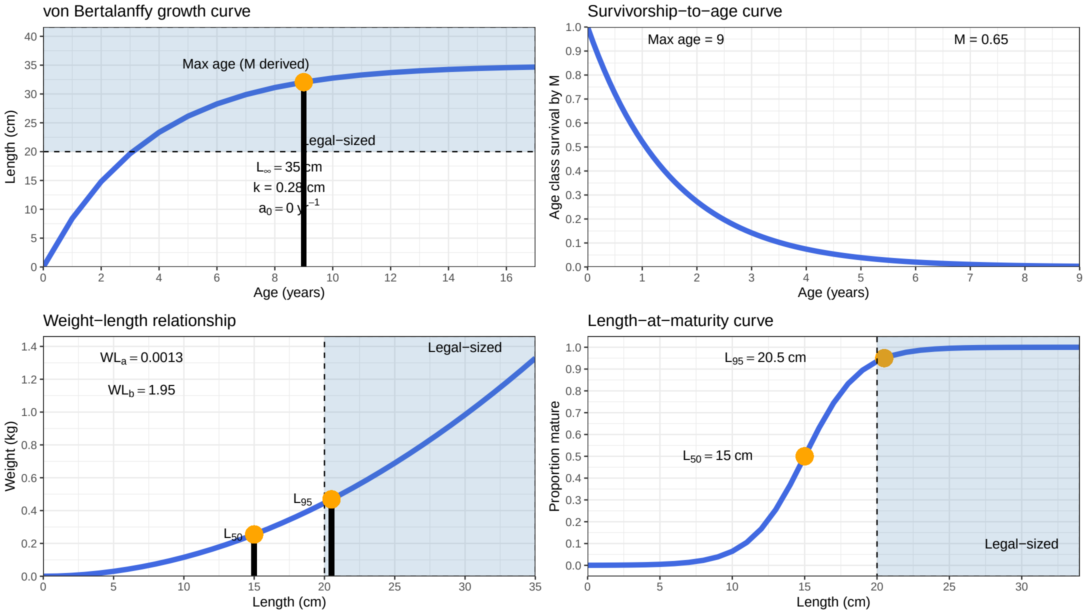

Figure B.3: Life history defined by mean parameters specified for the blackfish operating model

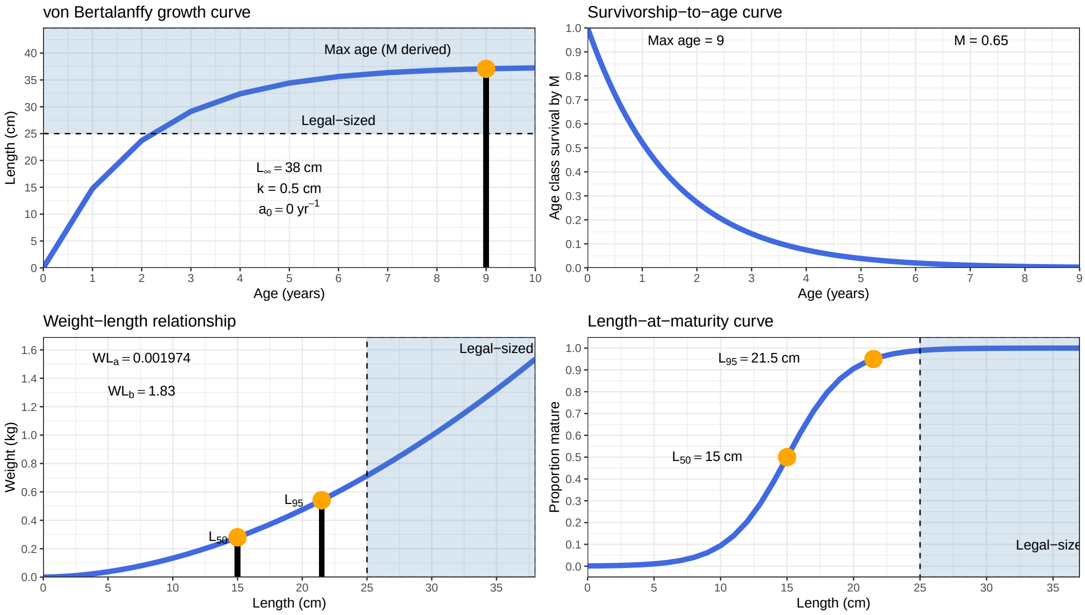

Figure B.4: Life history defined by mean parameters specified for the brown sandfish operating model

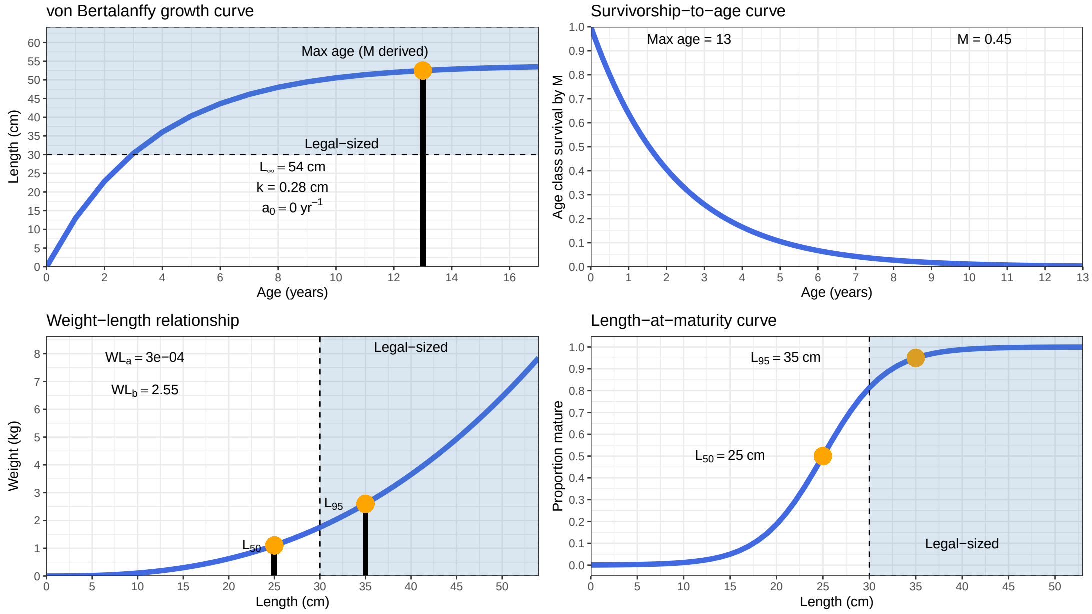

Figure B.5: Life history defined by mean parameters specified for the black teatfish operating model

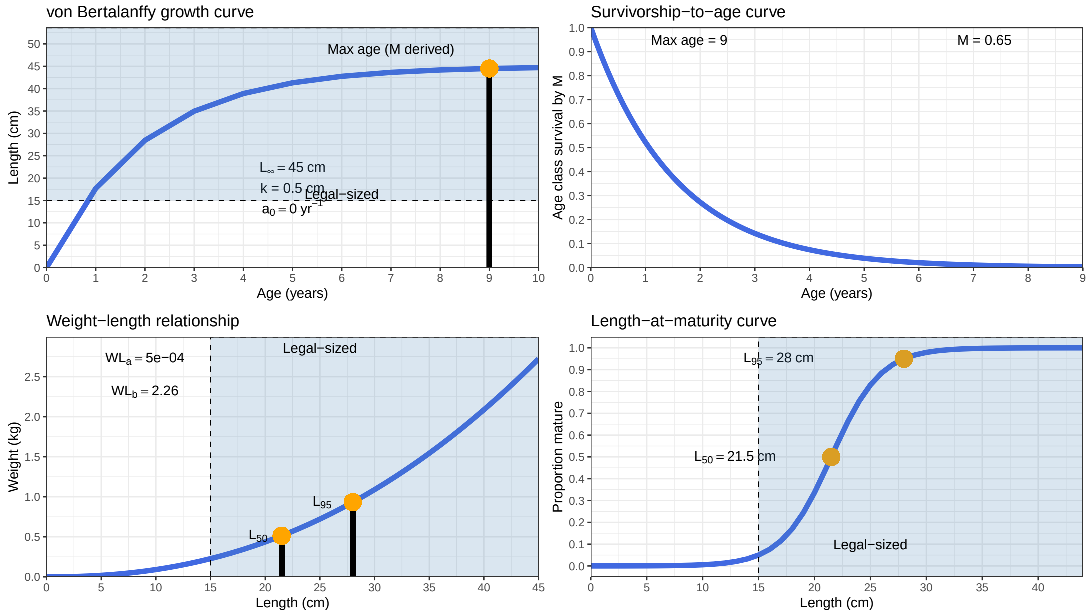

Figure B.6: Life history defined by mean parameters specified for the golden sandfish operating model

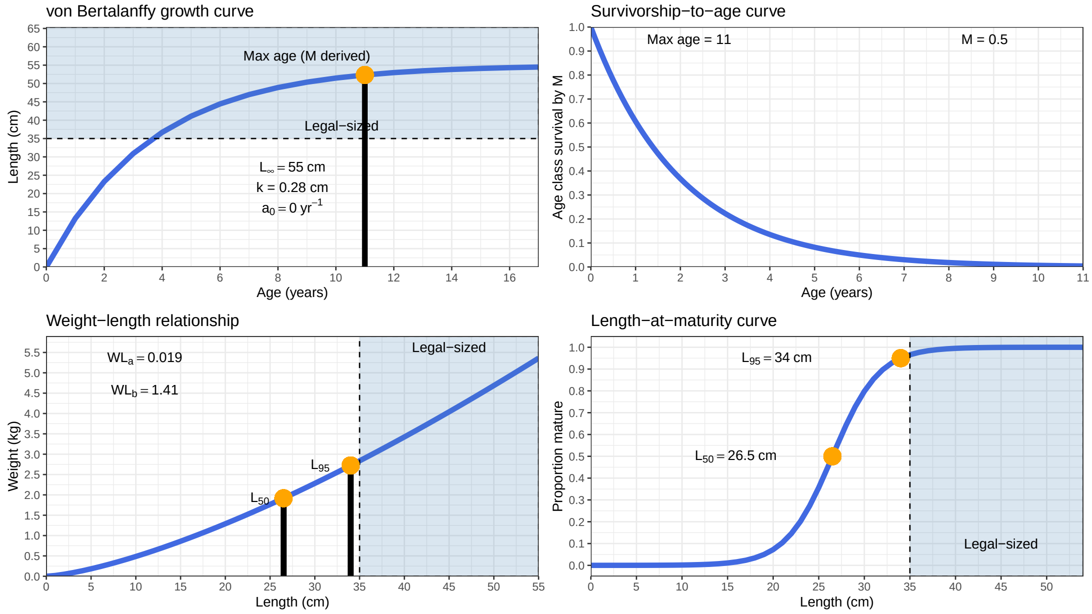

Figure B.7: Life history defined by mean parameters specified for the hermanni curryfish operating model

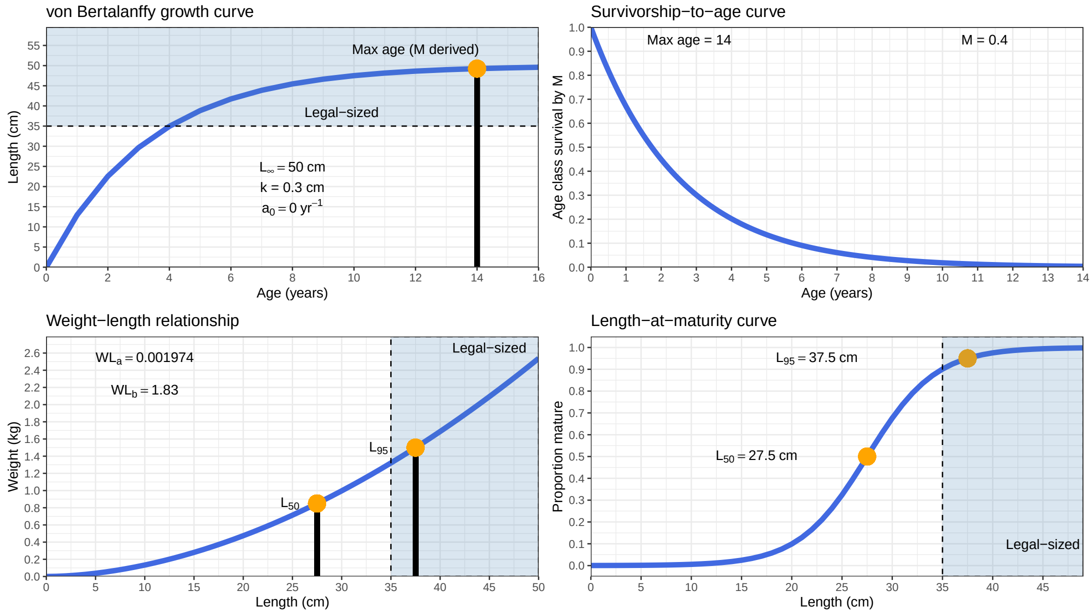

Figure B.8: Life history defined by mean parameters specified for the leopardfish operating model

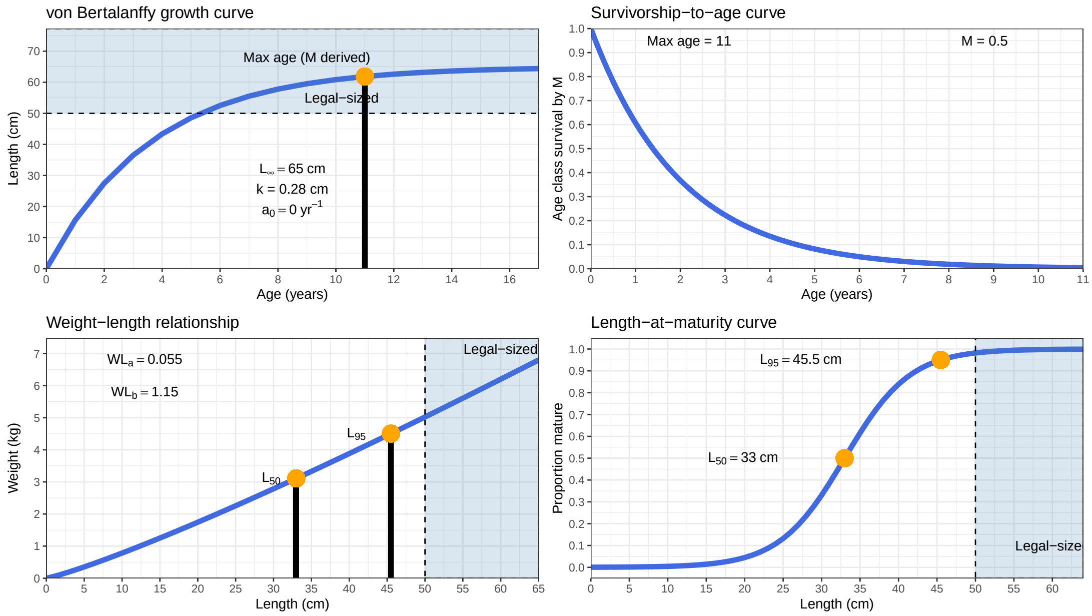

Figure B.9: Life history defined by mean parameters specified for the prickly redfish operating model

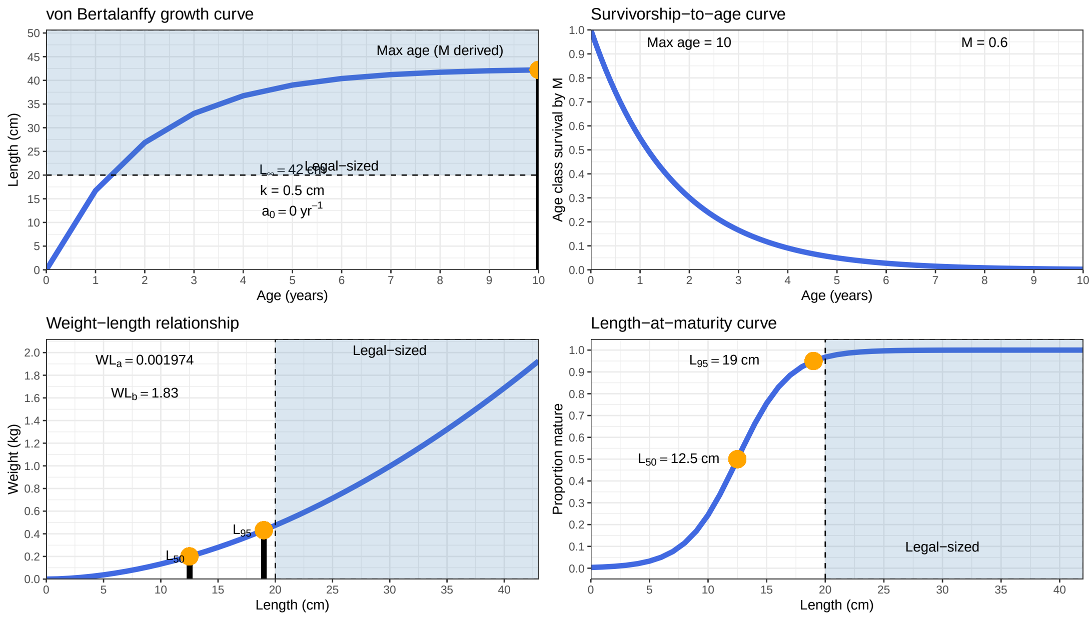

Figure B.10: Life history defined by mean parameters specified for the sandfish operating model

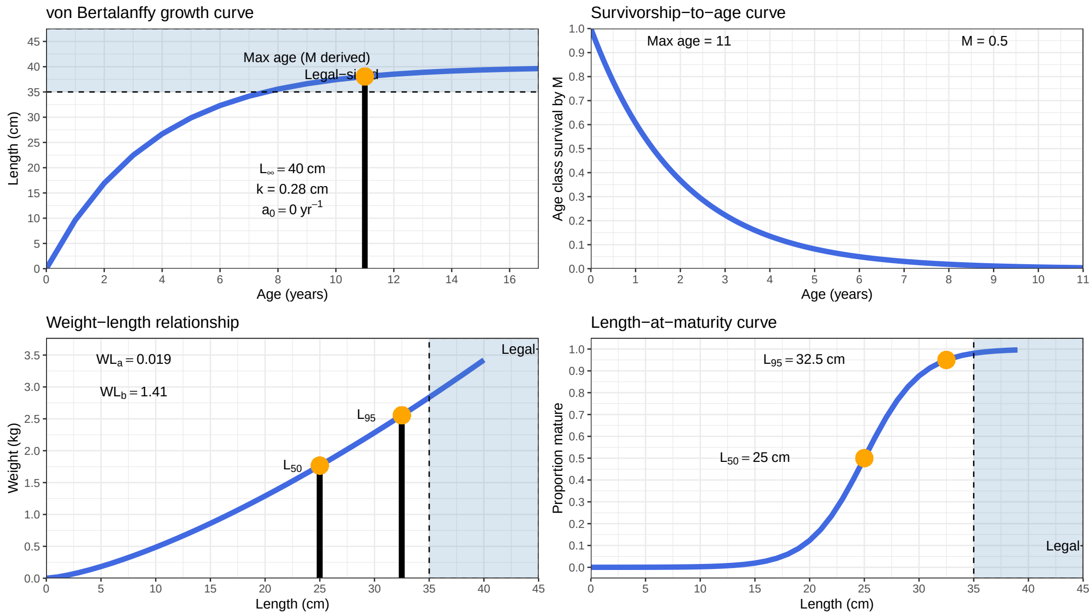

Figure B.11: Life history defined by mean parameters specified for the vastus curryfish operating model

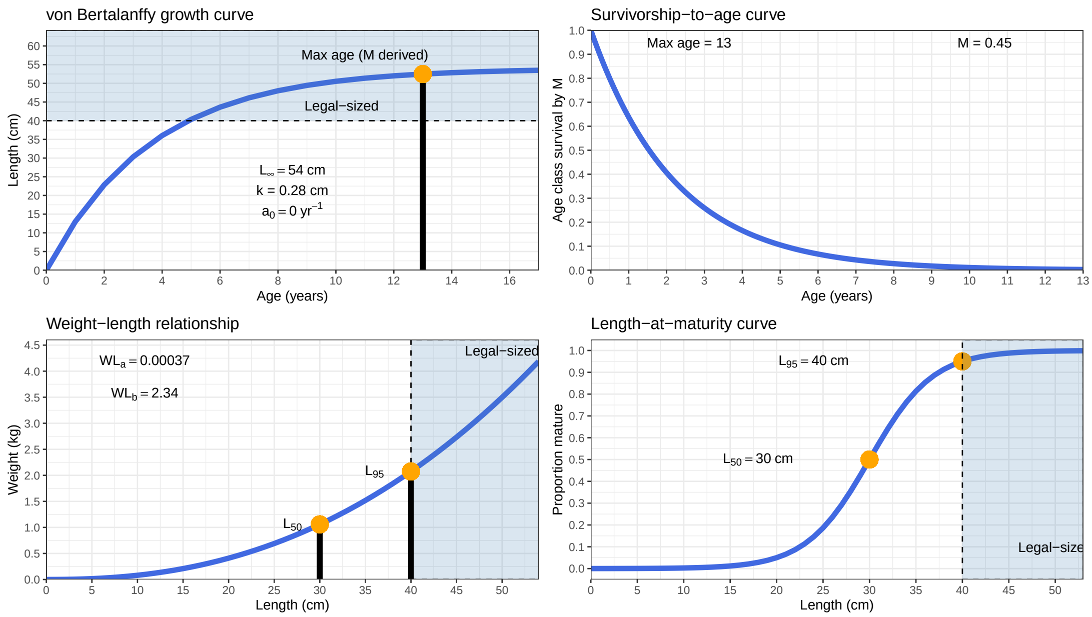

Figure B.12: Life history defined by mean parameters specified for the white teatfish operating model

Appendix C Biomass projection

C.1 Burrowing blackfish – Bunker

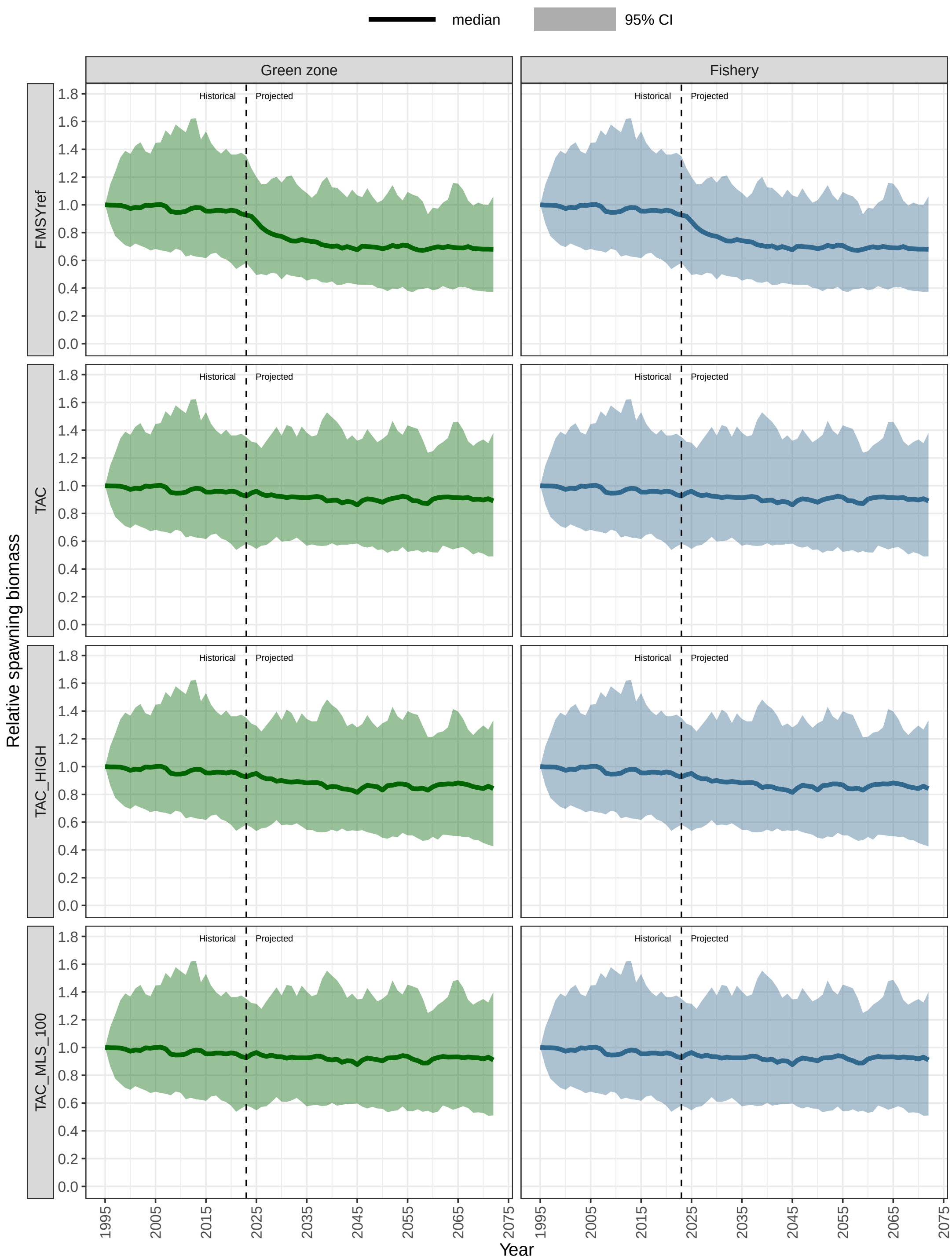

Figure C.1: Bunker projected biomass under management procedures without rotational harvest strategy

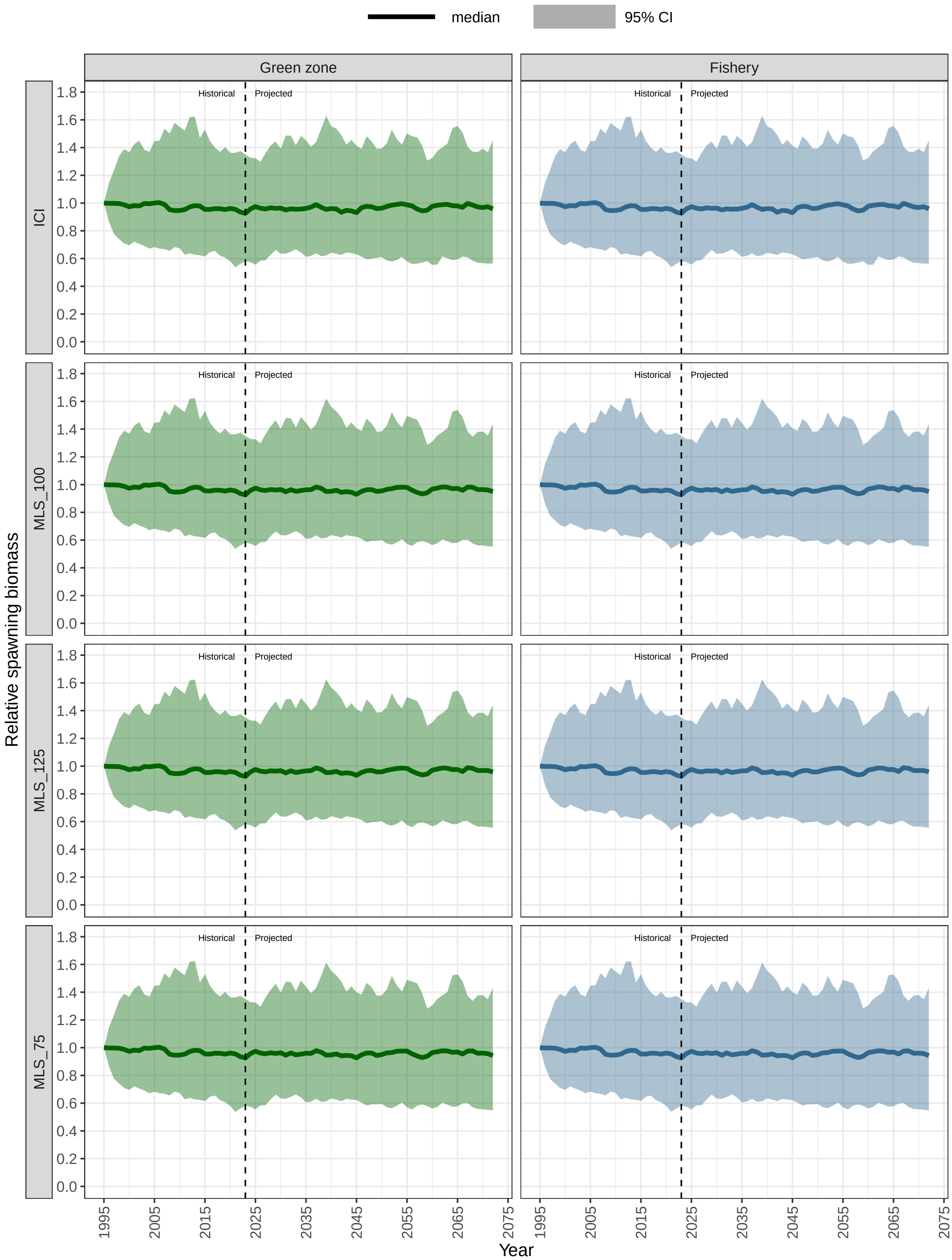

Figure C.2: Bunker projected biomass under management procedures without rotational harvest strategy

C.2 Burrowing blackfish – Gould

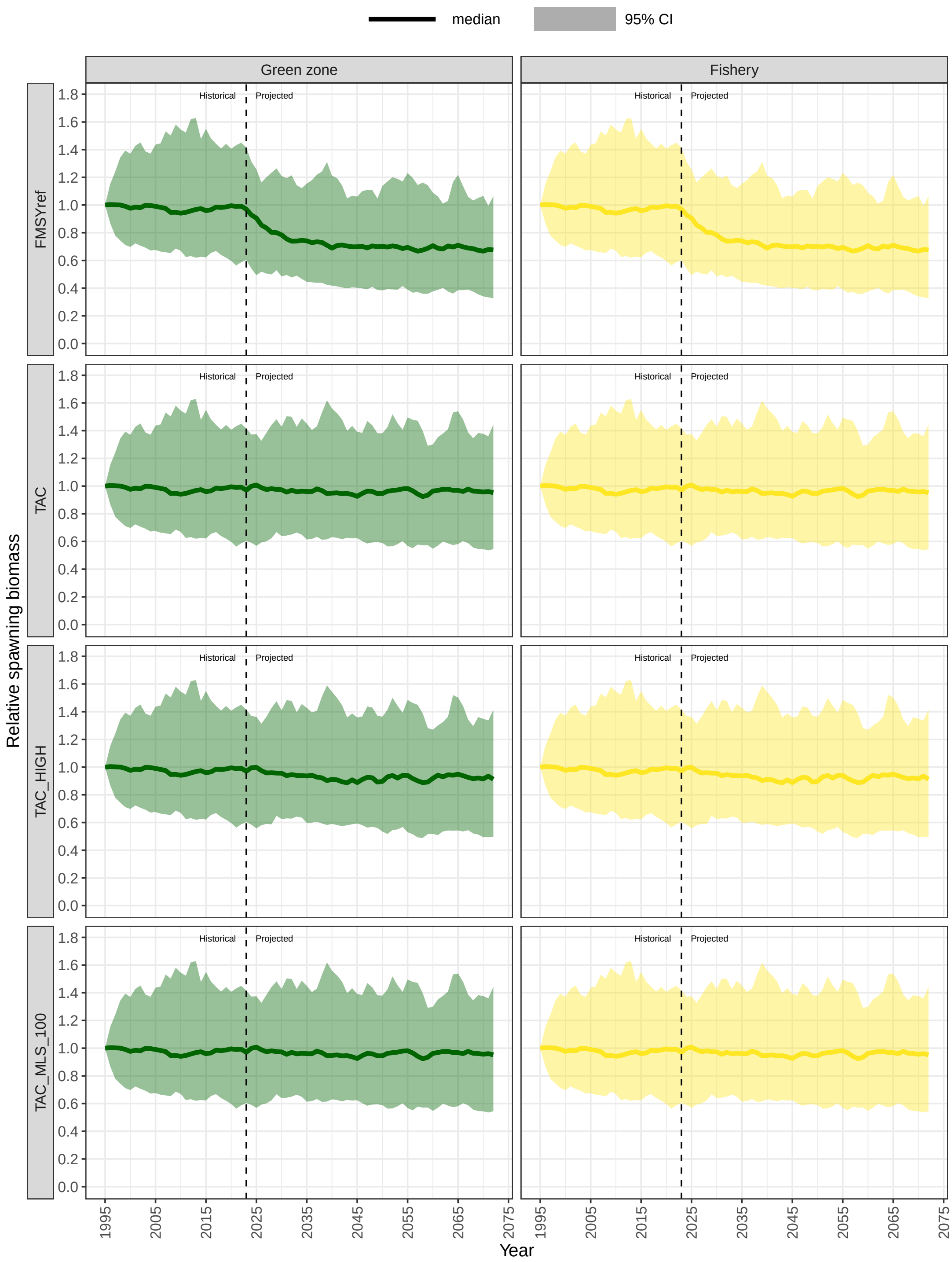

Figure C.3: Gould projected biomass under management procedures without rotational harvest strategy

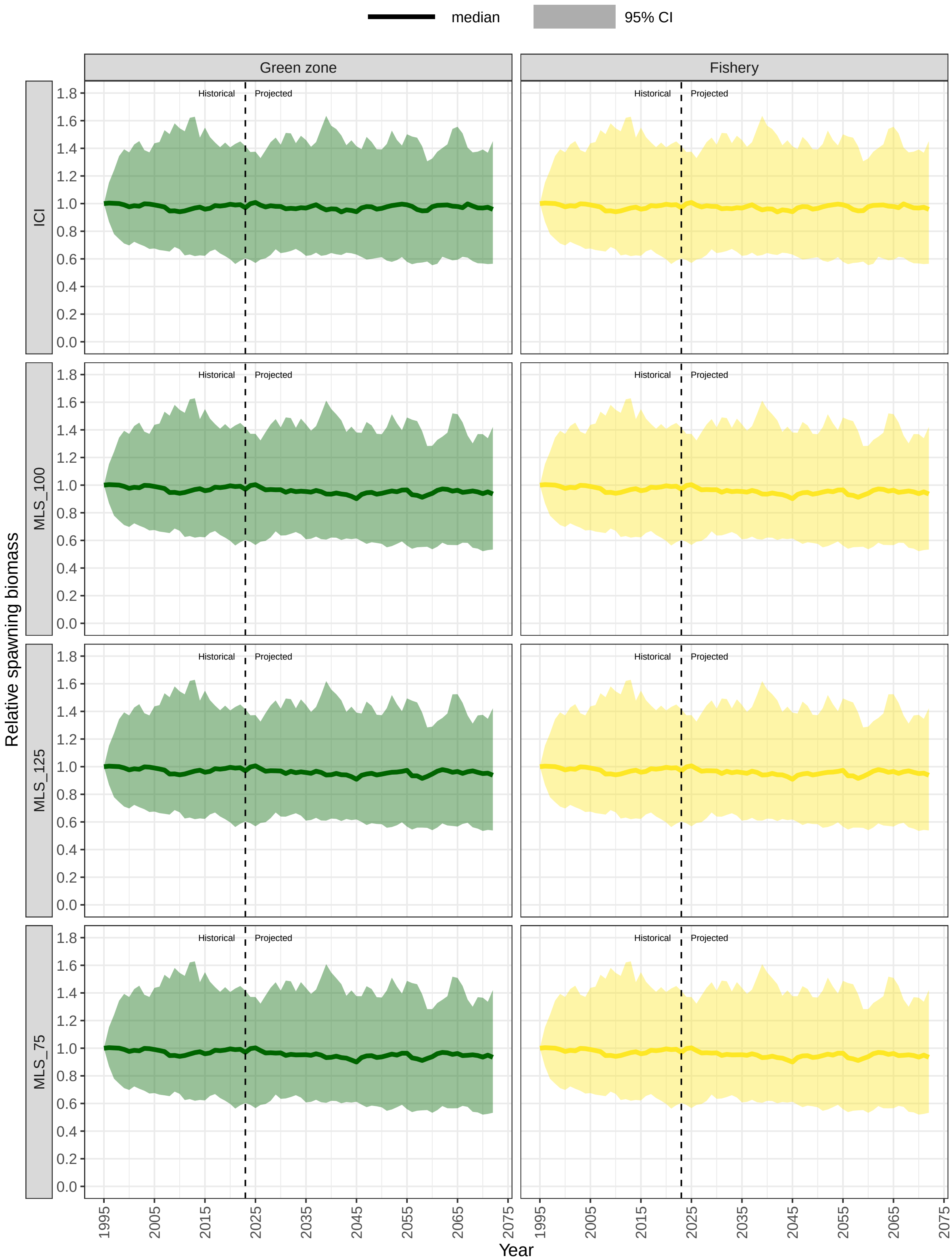

Figure C.4: Gould projected biomass under management procedures without rotational harvest strategy

C.3 Amberfish

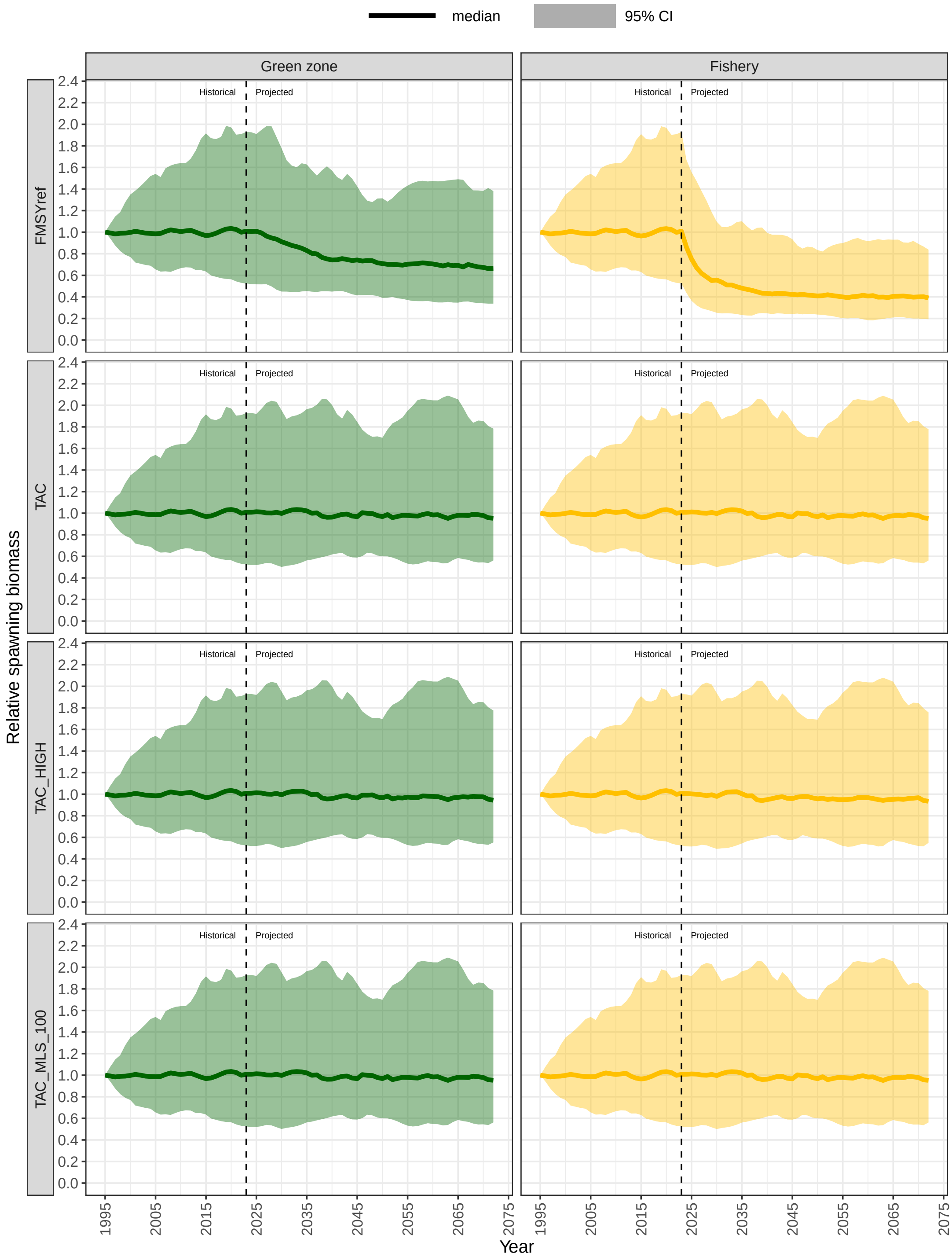

Figure C.5: Amberfish projected biomass under management procedures without rotational harvest strategy

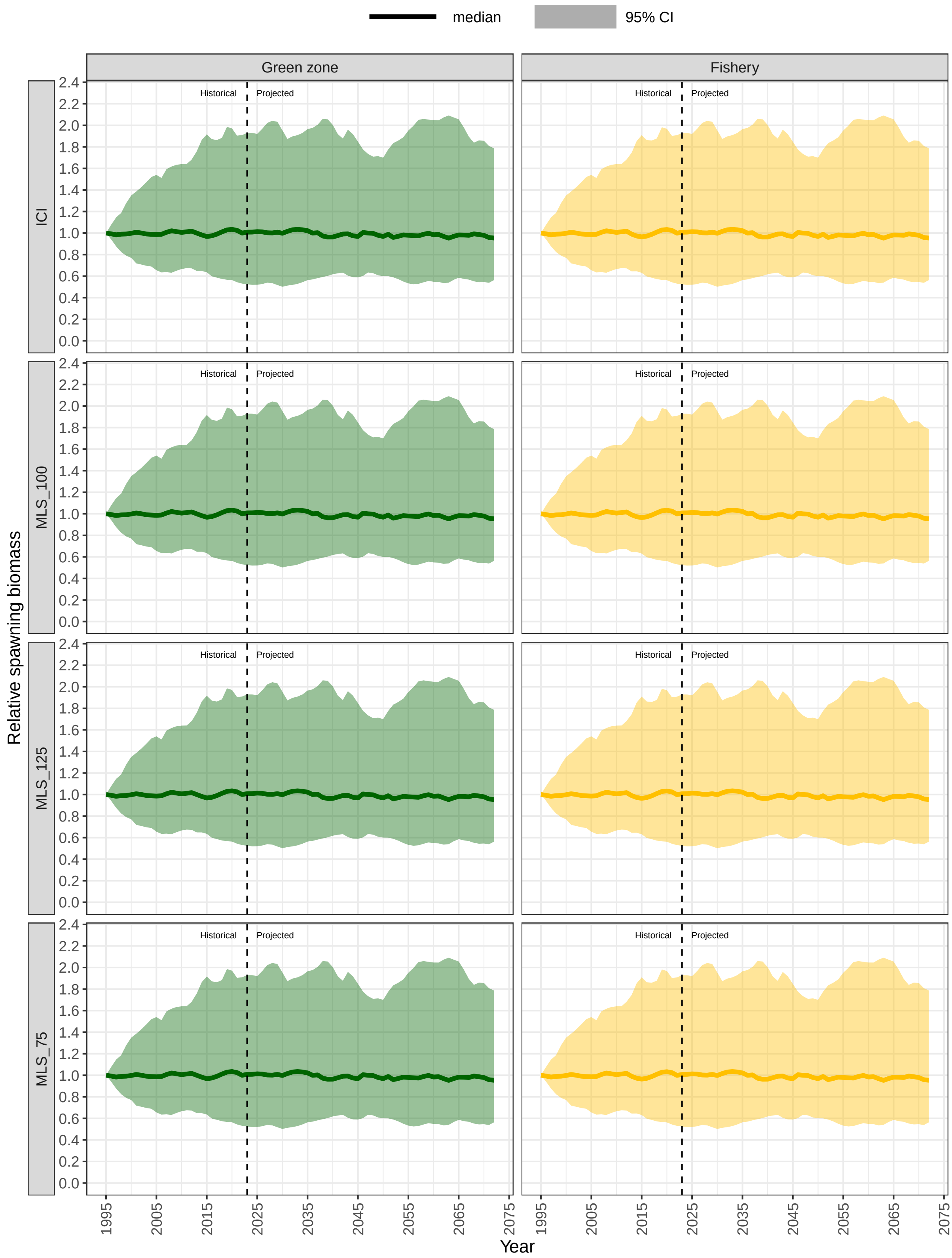

Figure C.6: Amberfish projected biomass under management procedures without rotational harvest strategy

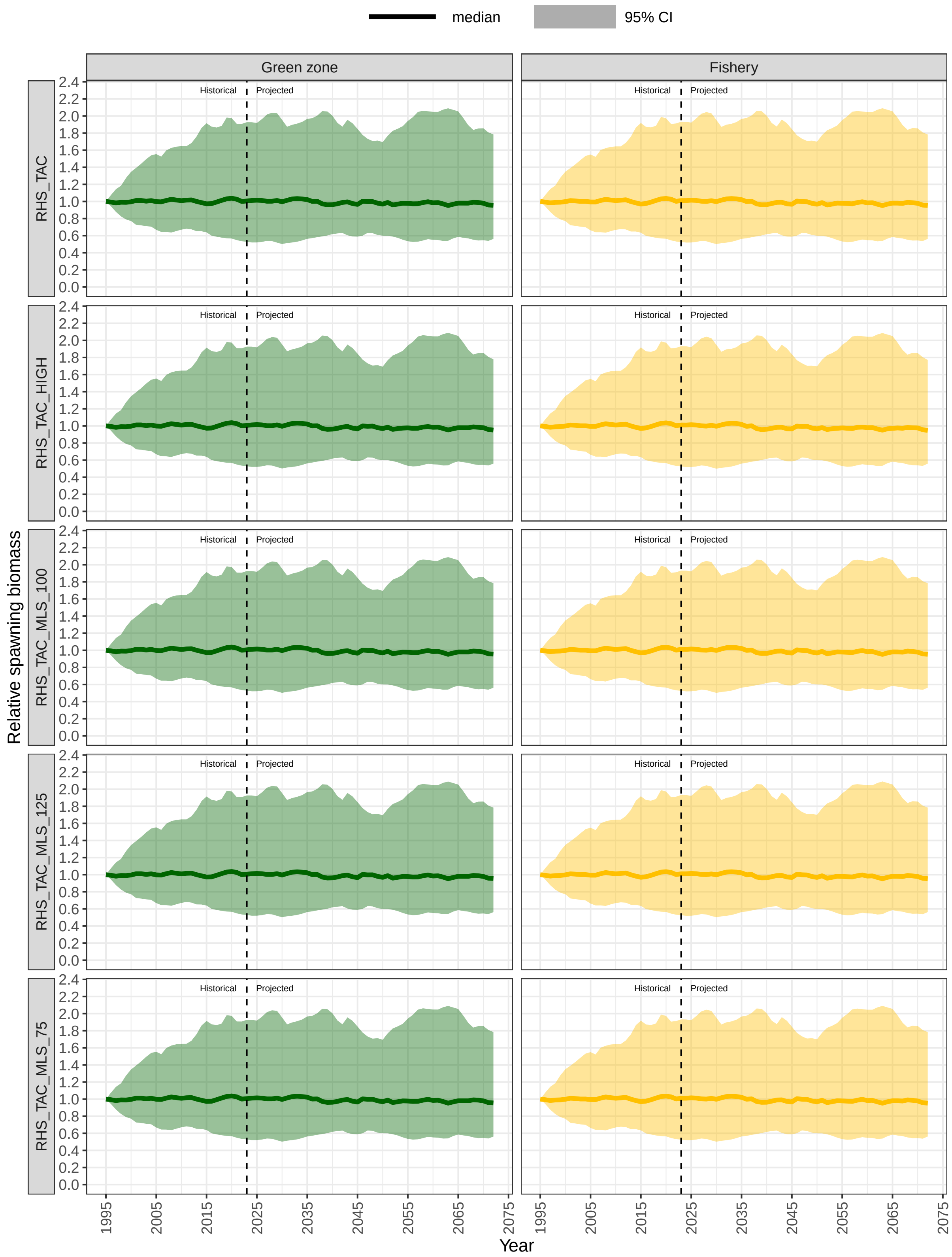

Figure C.7: Amberfish projected biomass under management procedures with rotational harvest strategy

C.4 Blackfish

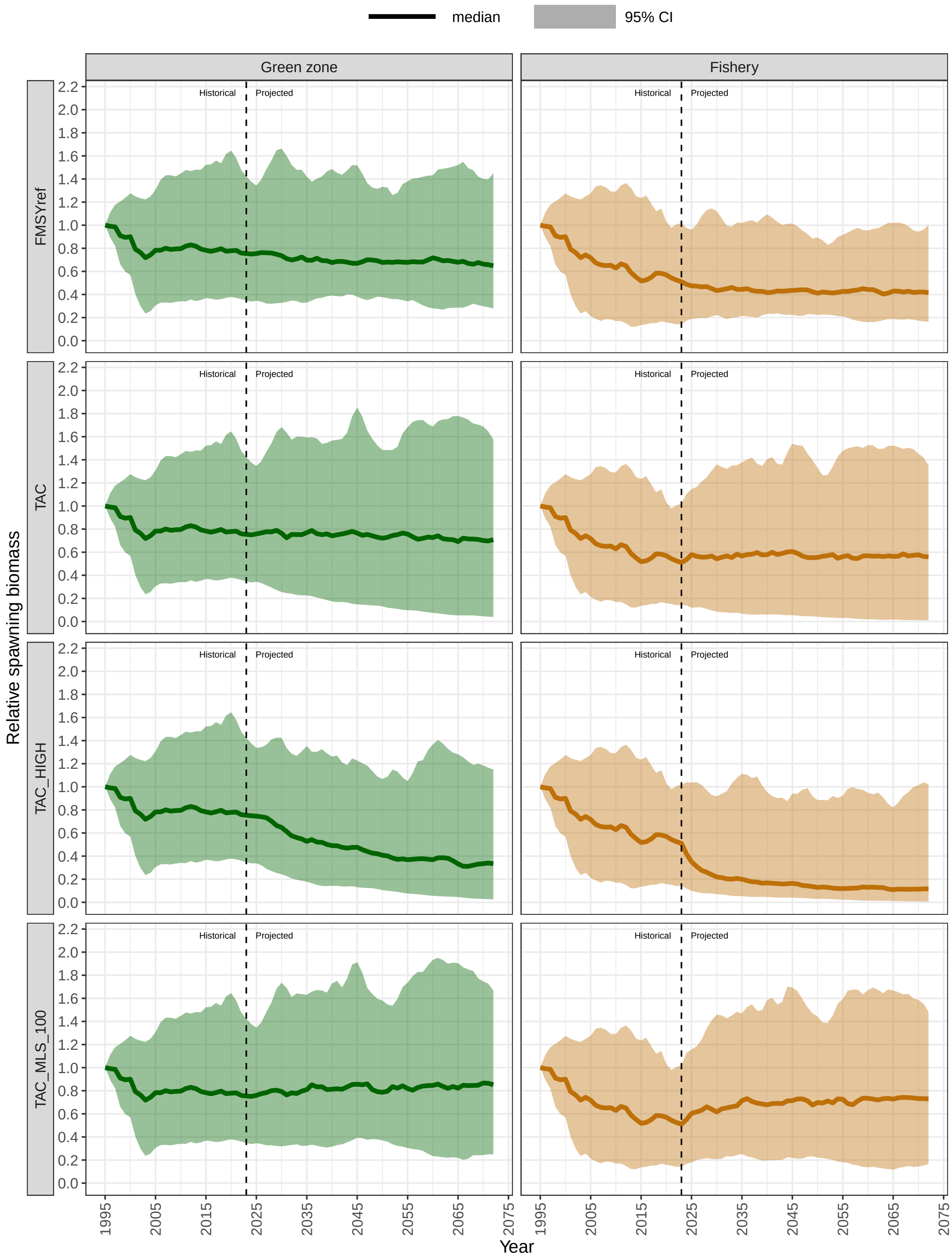

Figure C.8: Blackfish projected biomass under management procedures without rotational harvest strategy

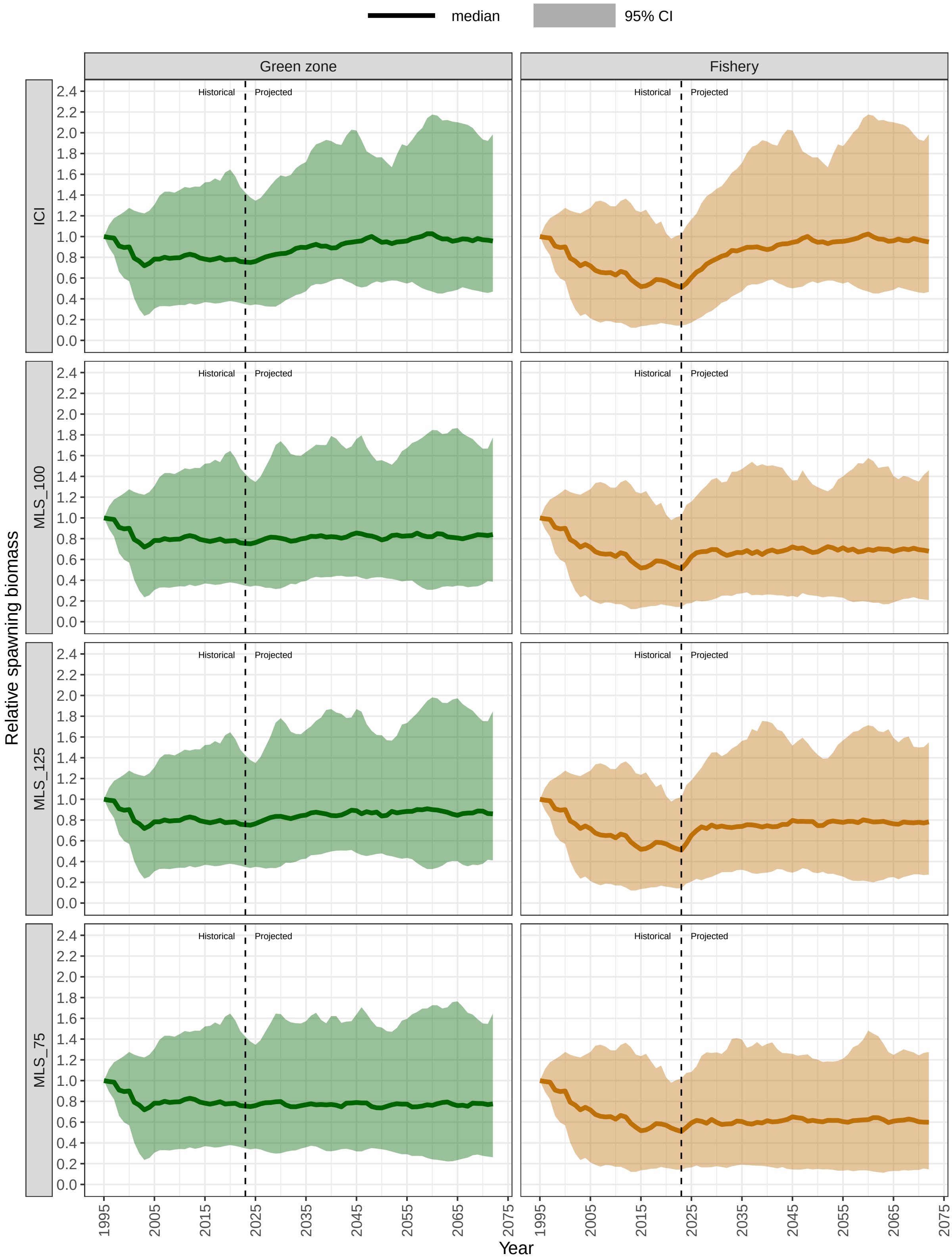

Figure C.9: Blackfish projected biomass under management procedures without rotational harvest strategy

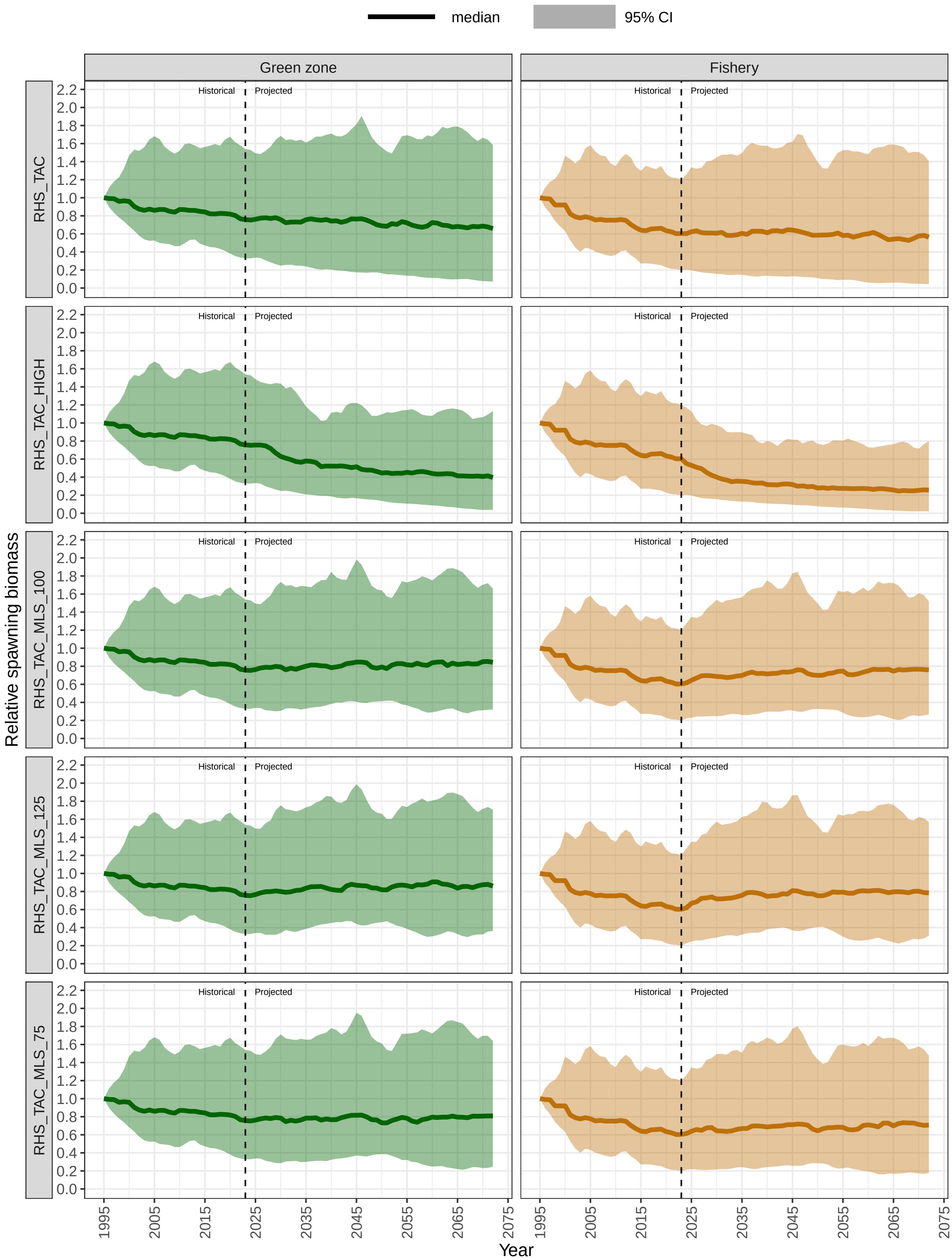

Figure C.10: Blackfish projected biomass under management procedures with rotational harvest strategy

C.5 Brown sandfish

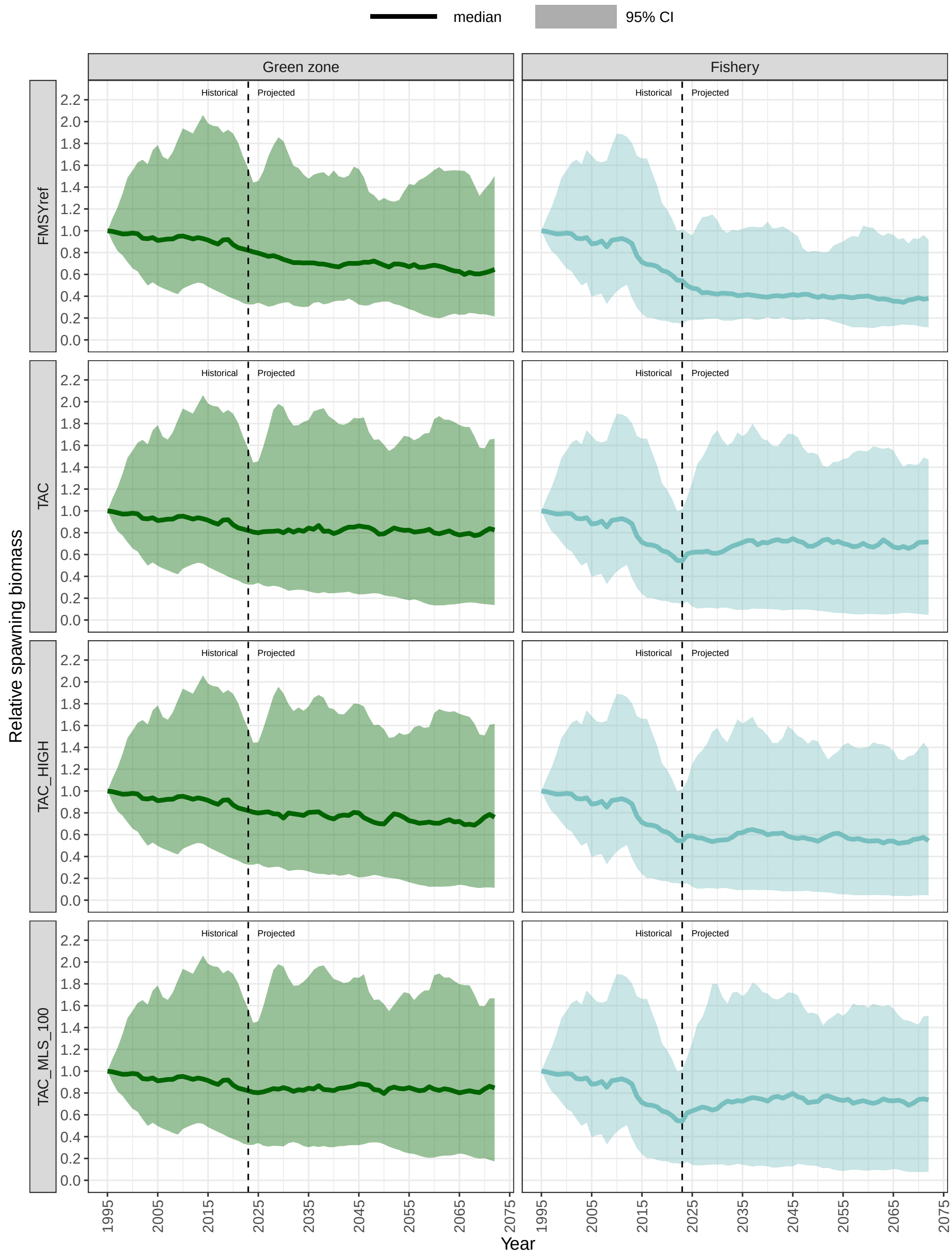

Figure C.11: Brown sandfish projected biomass under management procedures without rotational harvest strategy

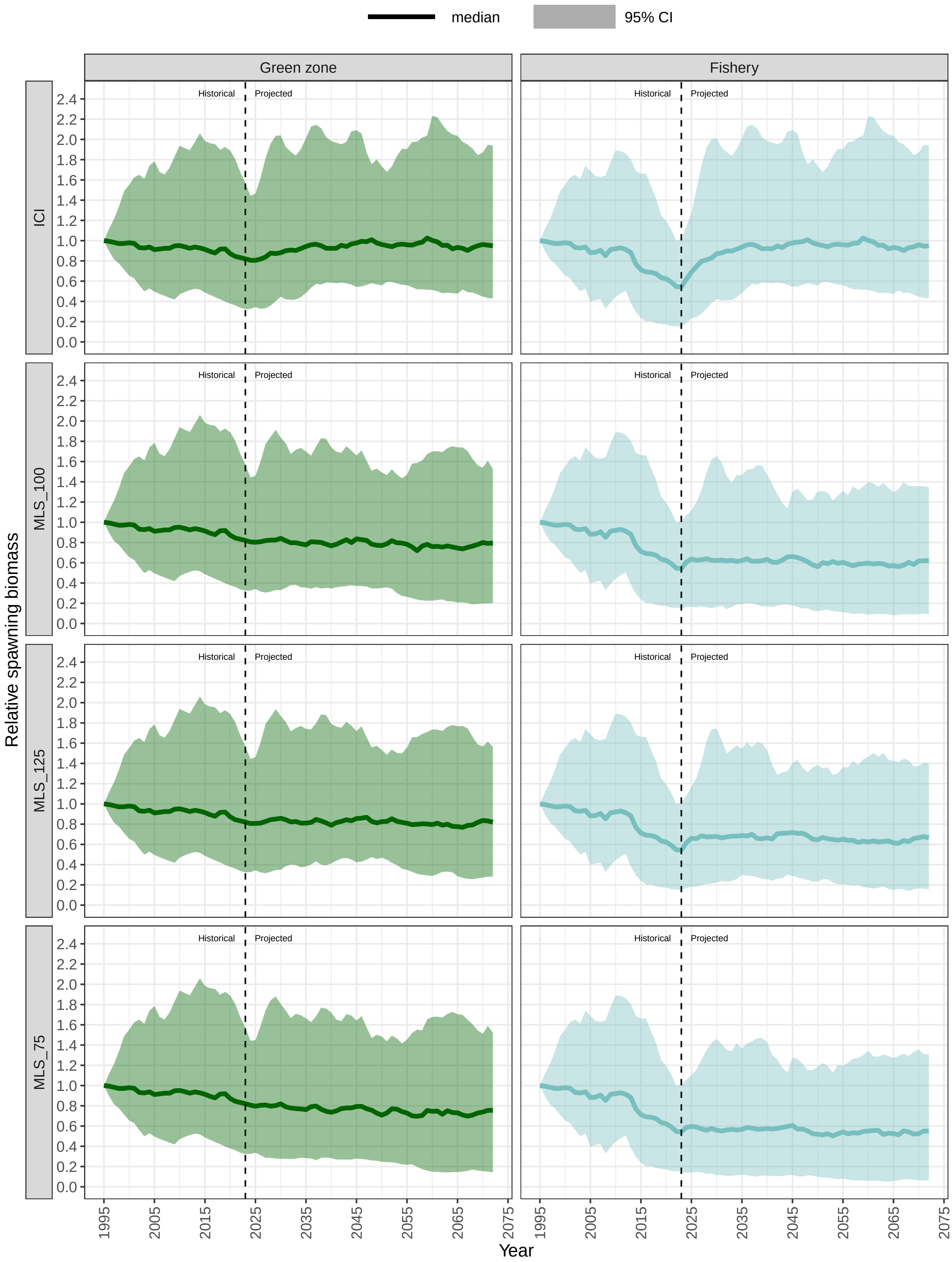

Figure C.12: Brown sandfish projected biomass under management procedures without rotational harvest strategy

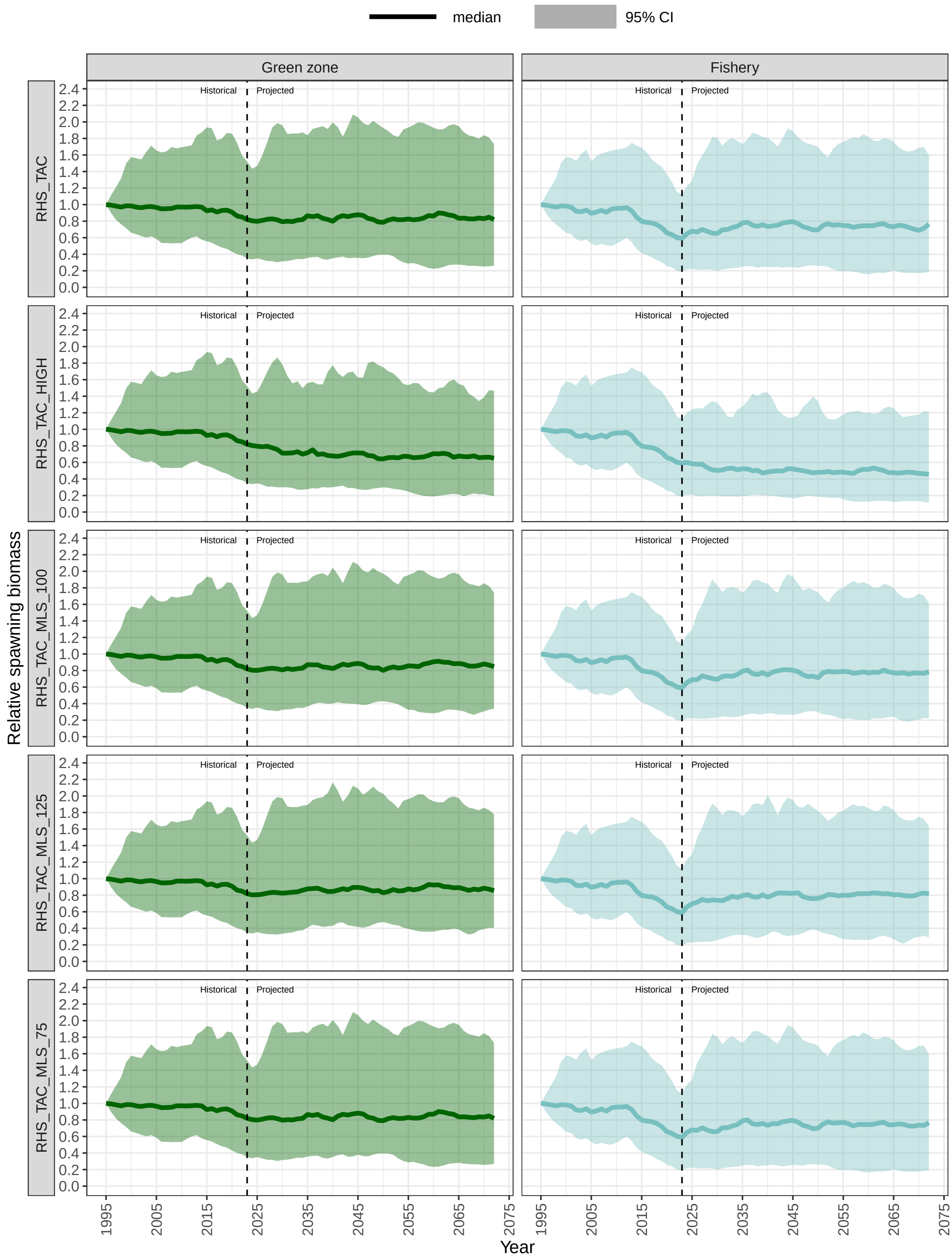

Figure C.13: Brown sandfish projected biomass under management procedures with rotational harvest strategy

C.6 Black teatfish

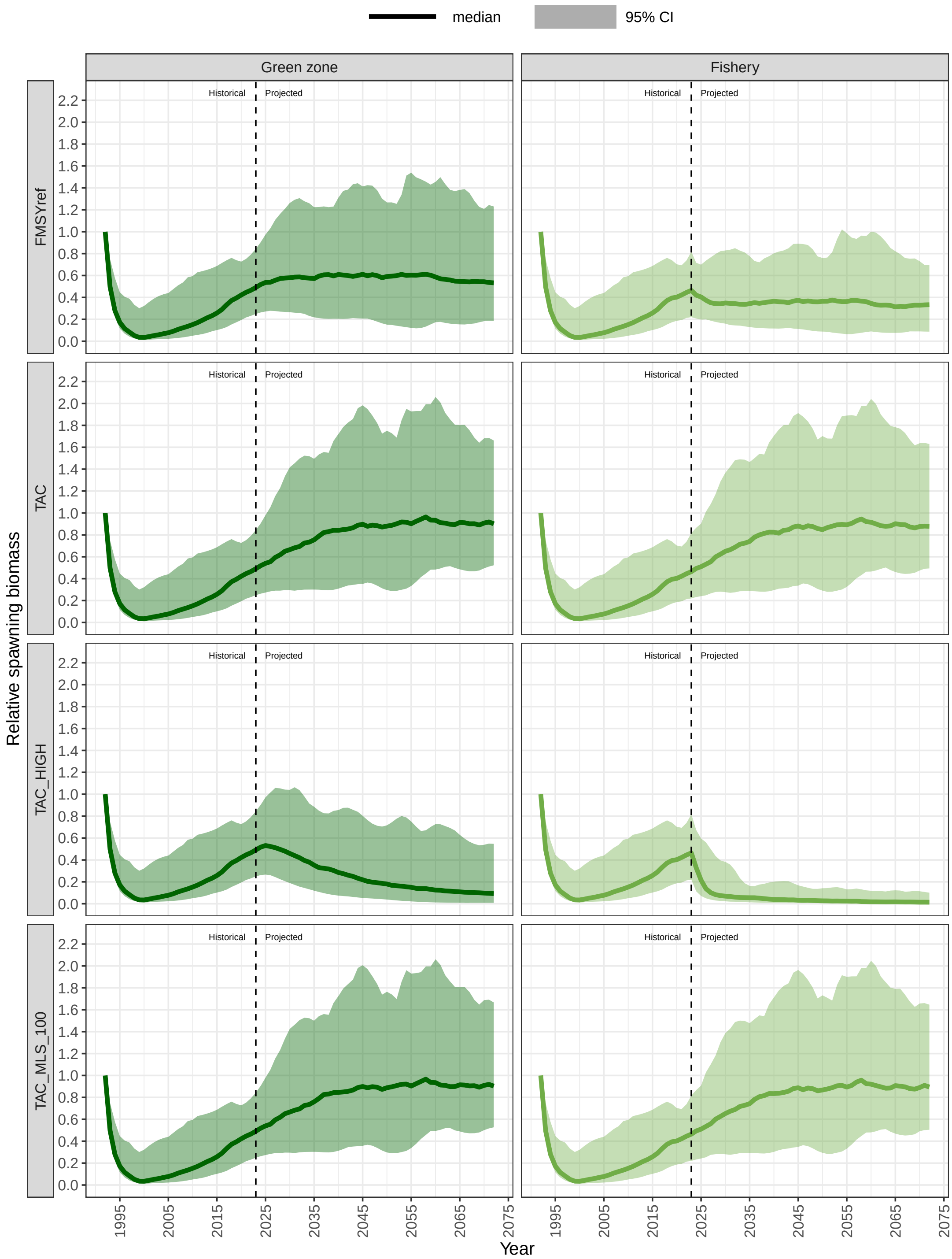

Figure C.14: Black teatfish projected biomass under management procedures without rotational harvest strategy

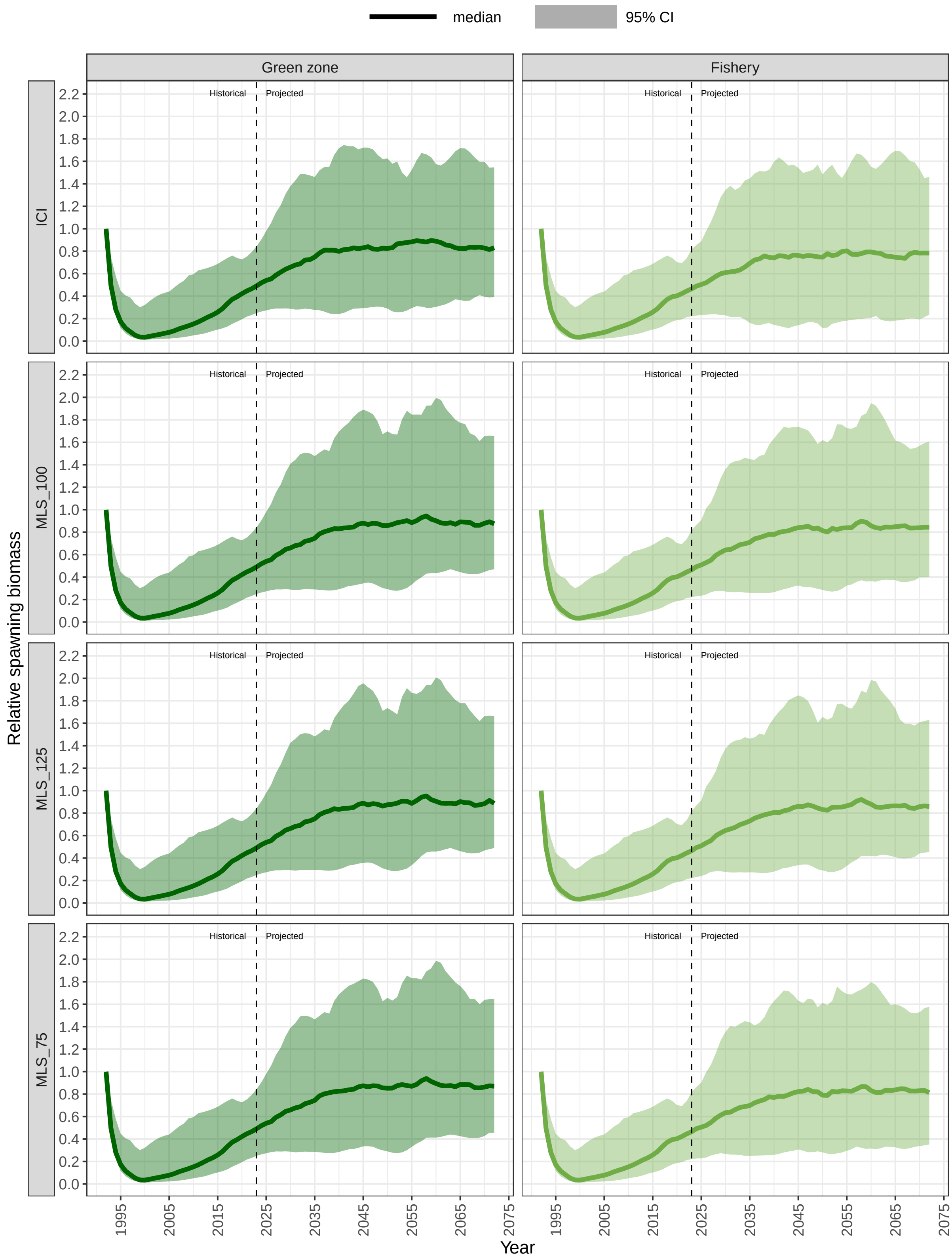

Figure C.15: Black teatfish projected biomass under management procedures without rotational harvest strategy

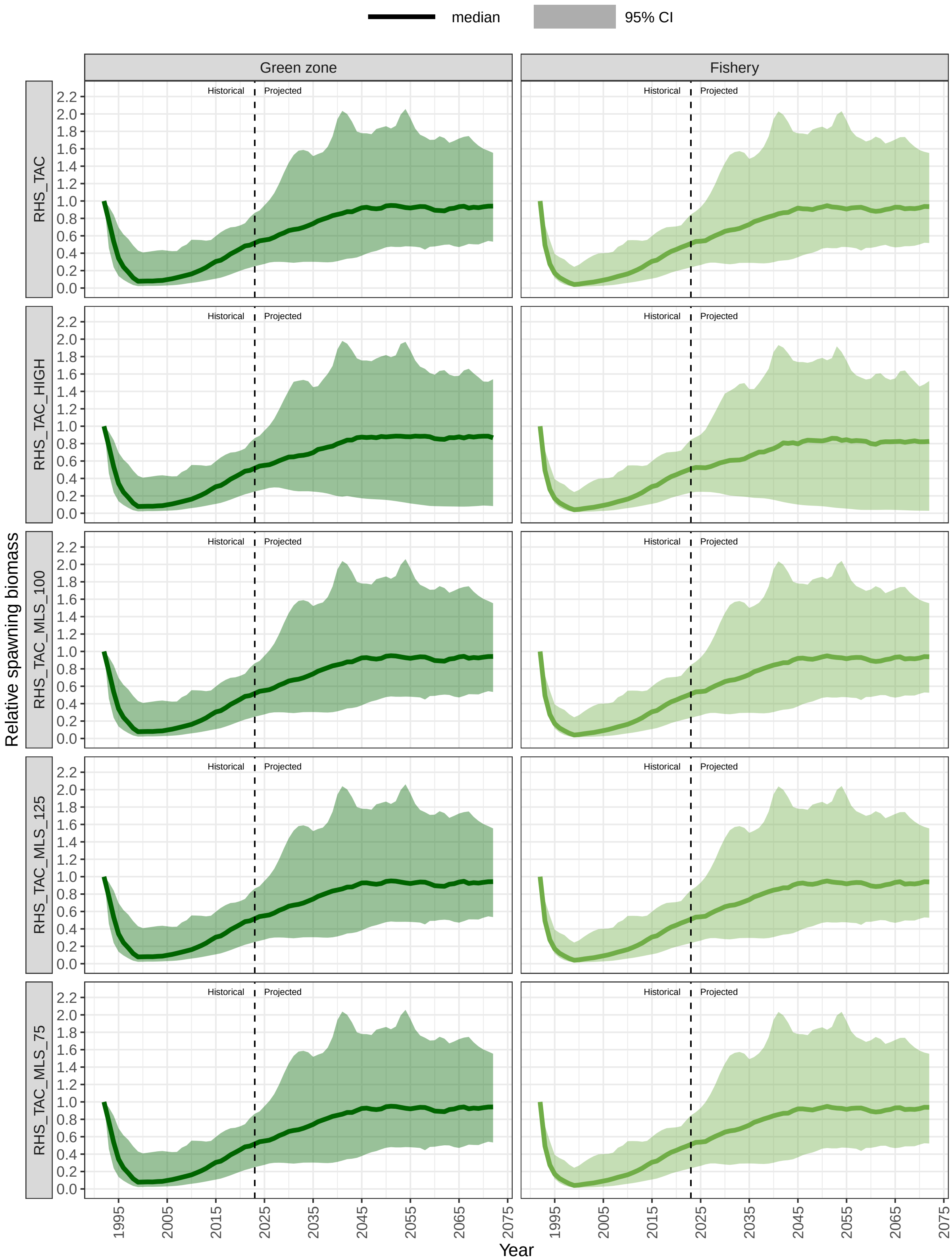

Figure C.16: Black teatfish projected biomass under management procedures with rotational harvest strategy

C.7 Golden sandfish

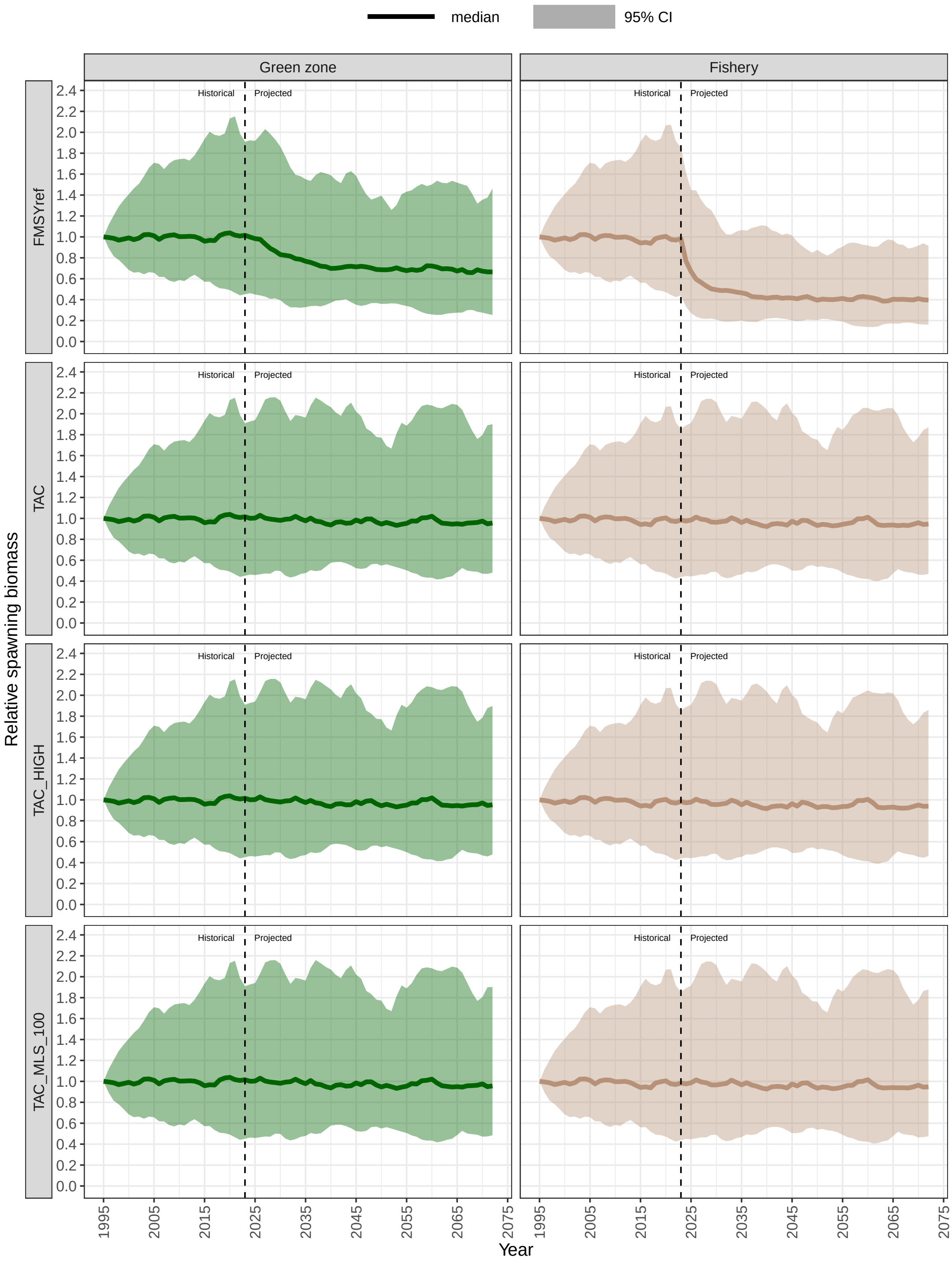

Figure C.17: Golden sandfish projected biomass under management procedures without rotational harvest strategy

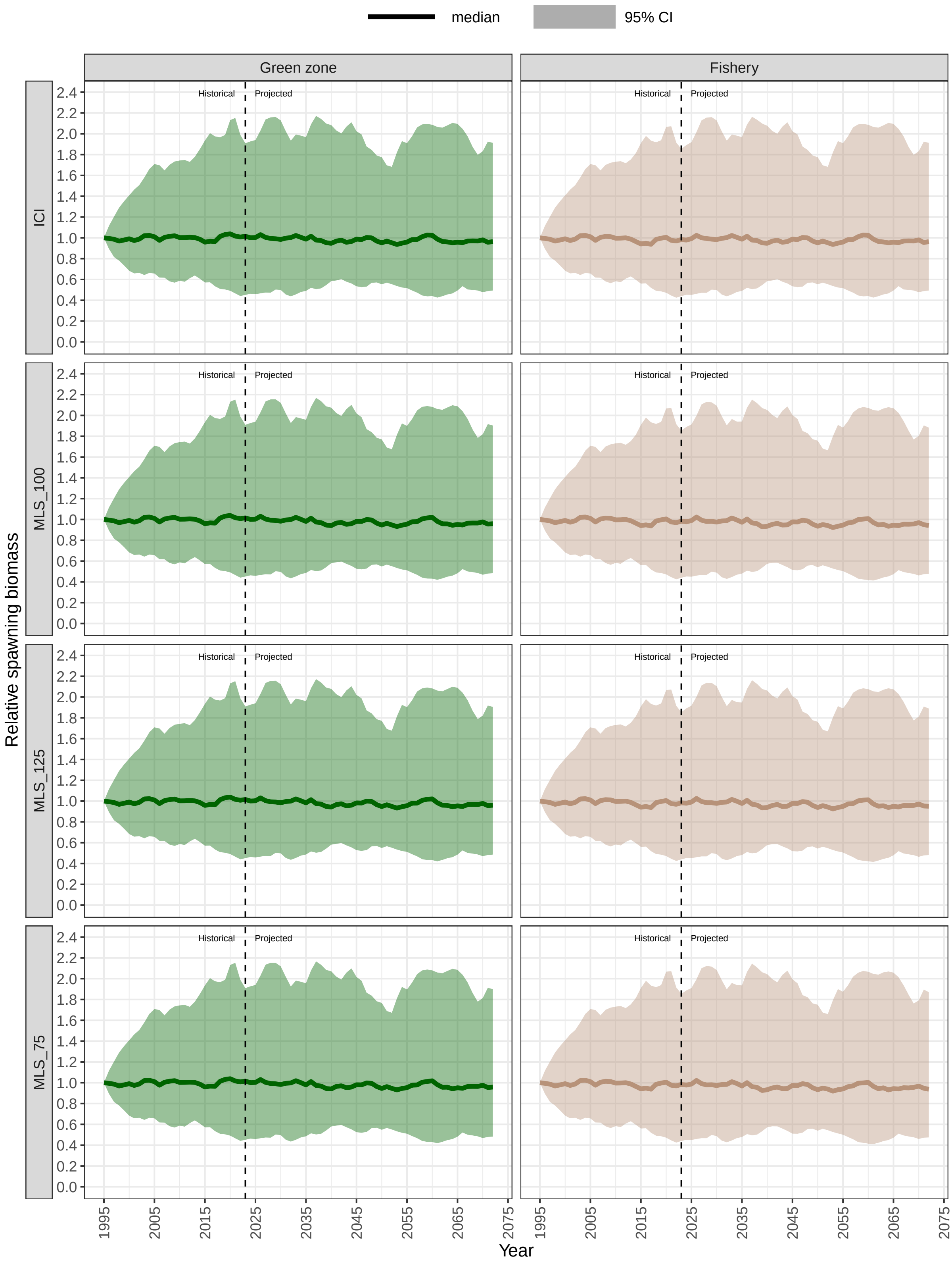

Figure C.18: Golden sandfish projected biomass under management procedures without rotational harvest strategy

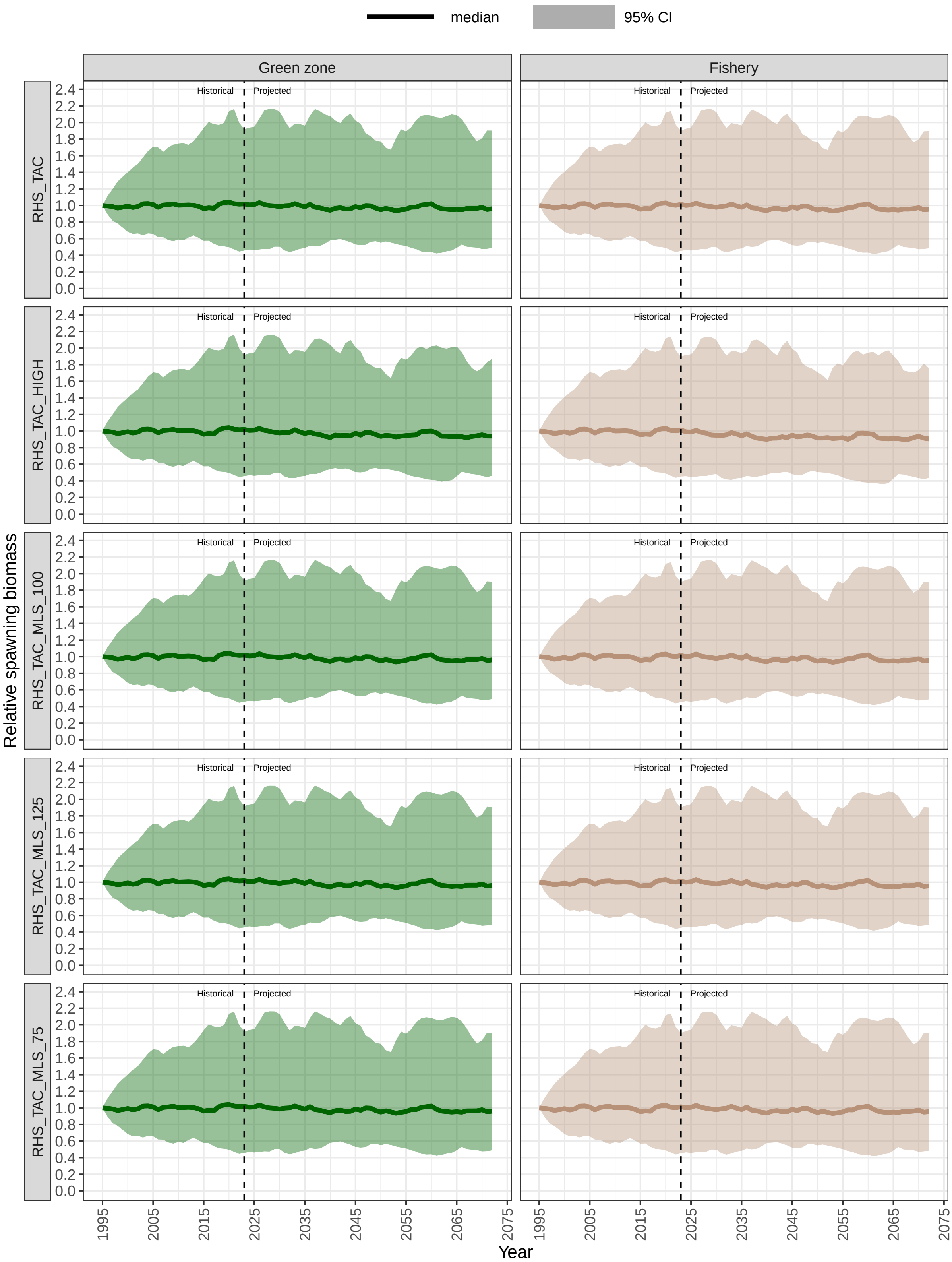

Figure C.19: Golden sandfish projected biomass under management procedures with rotational harvest strategy

C.8 Hermanni curryfish

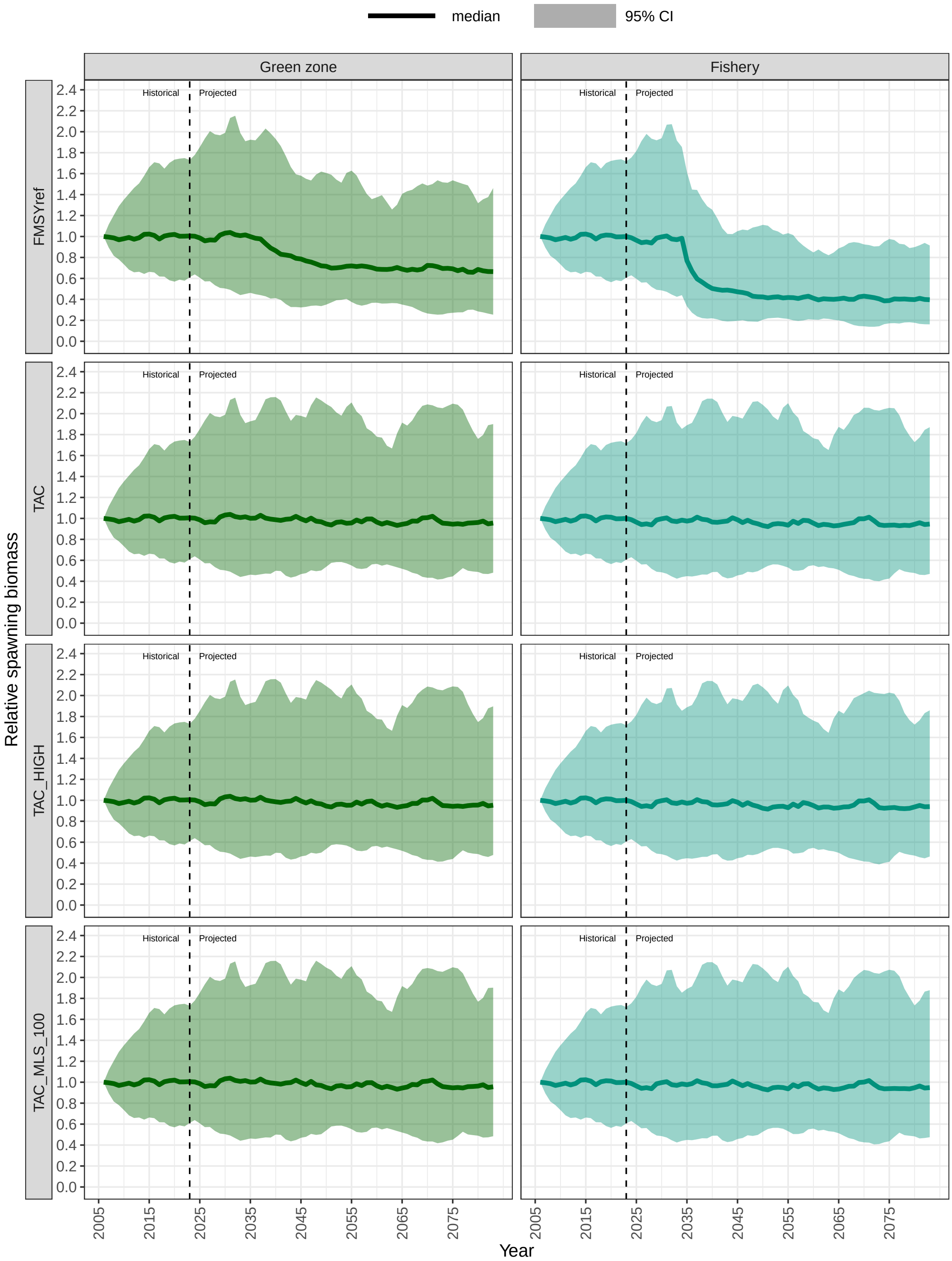

Figure C.20: Hermanni curryfish projected biomass under management procedures without rotational harvest strategy

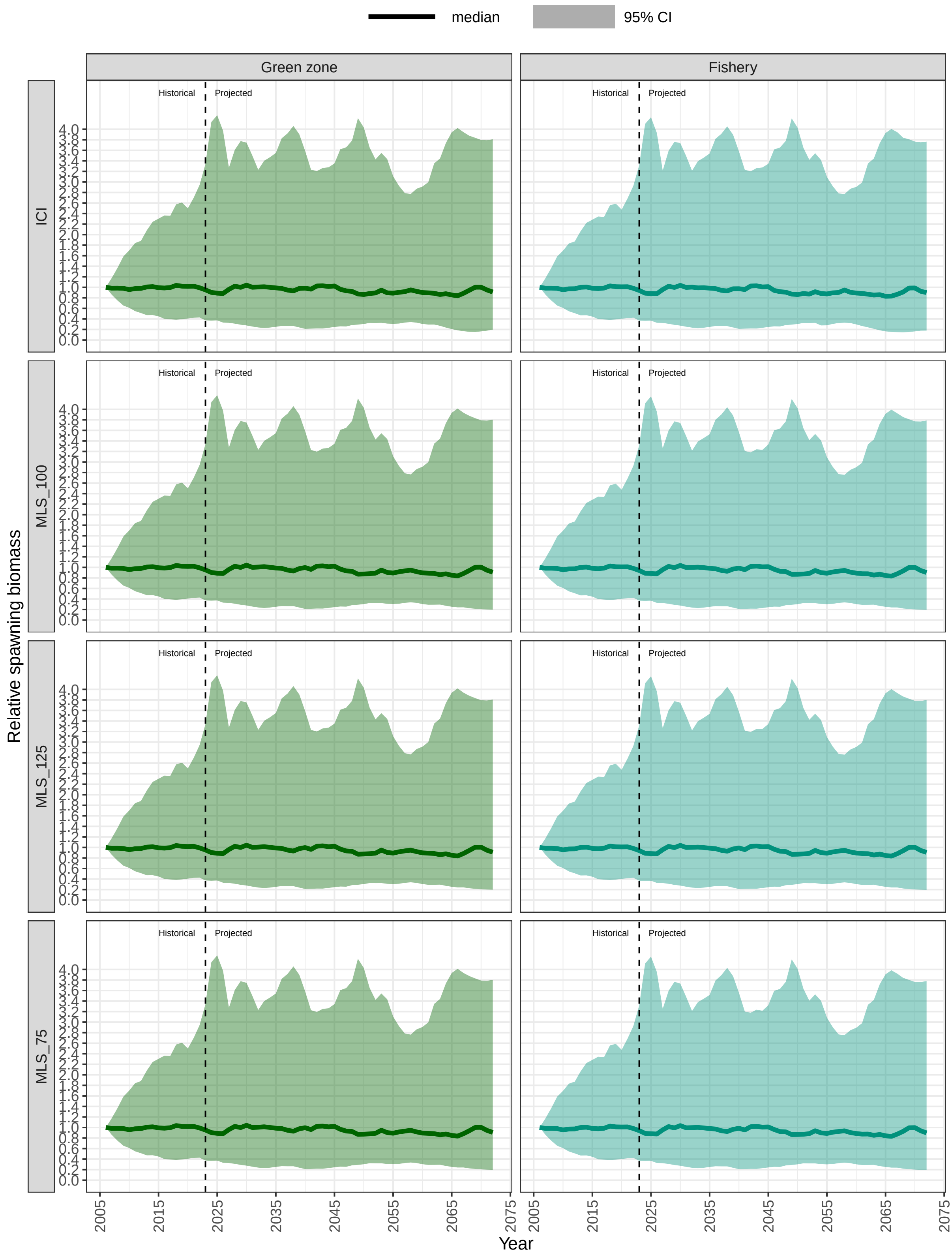

Figure C.21: Hermanni curryfish projected biomass under management procedures without rotational harvest strategy

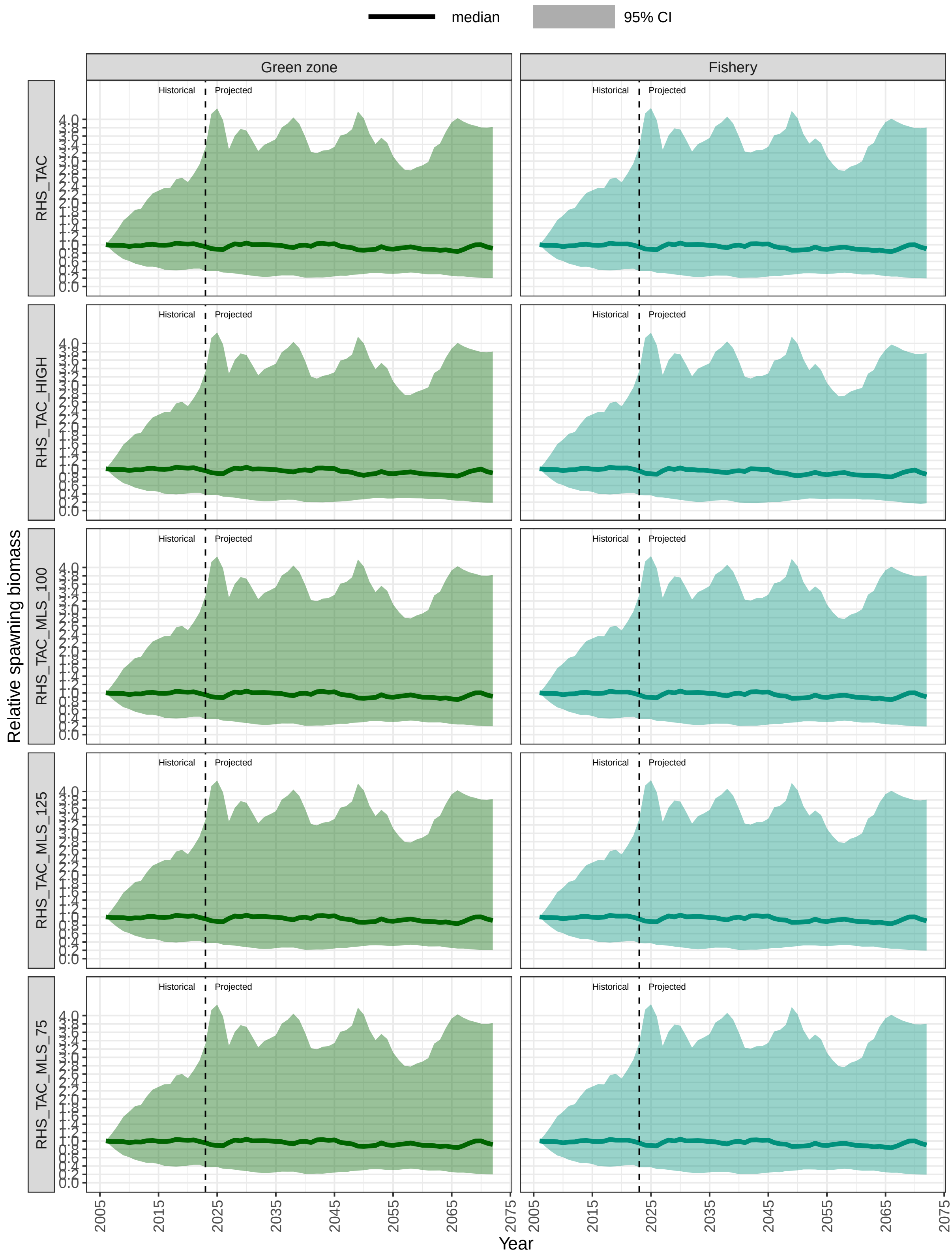

Figure C.22: Hermanni curryfish projected biomass under management procedures with rotational harvest strategy

C.9 Leopardfish

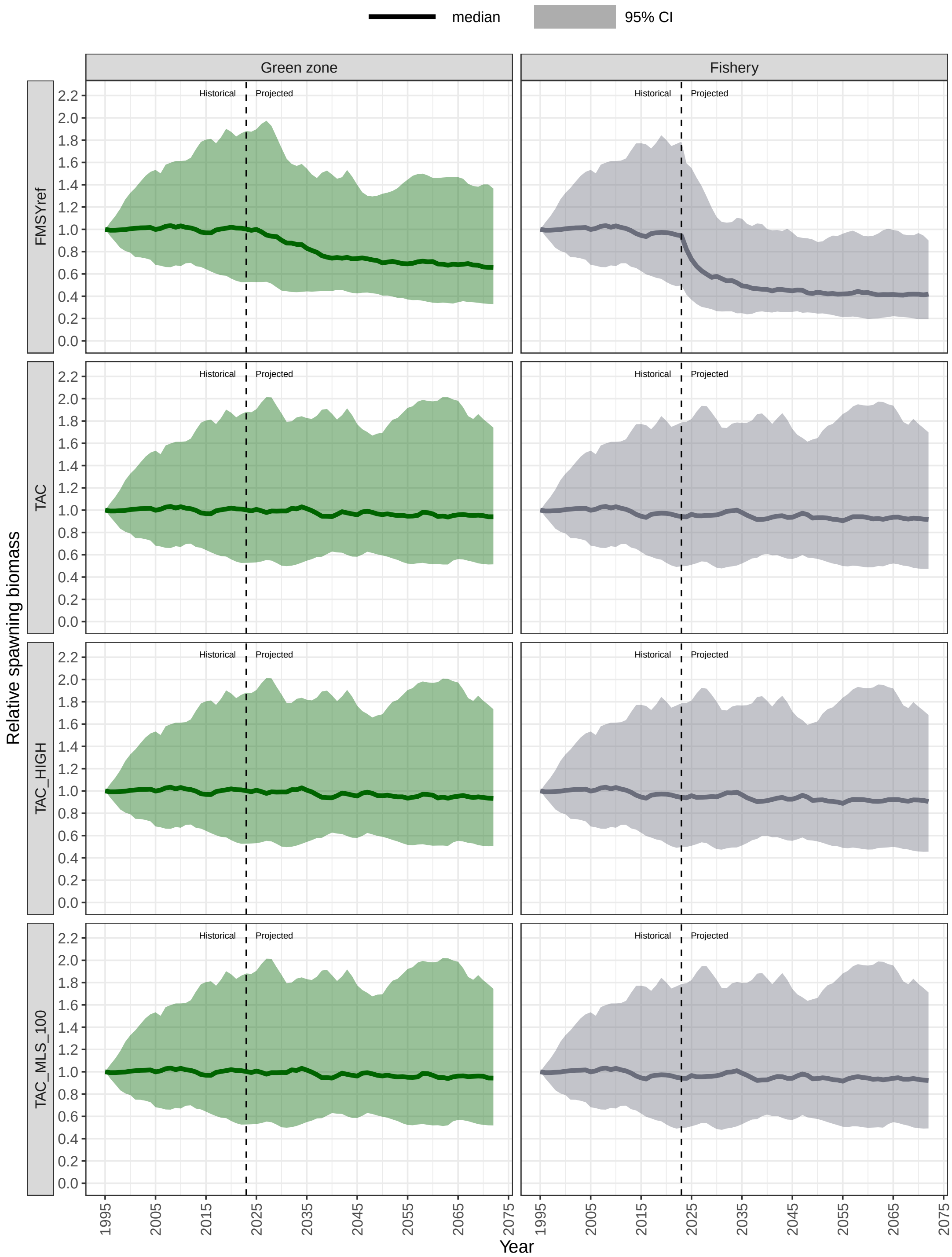

Figure C.23: Leopardfish projected biomass under management procedures without rotational harvest strategy

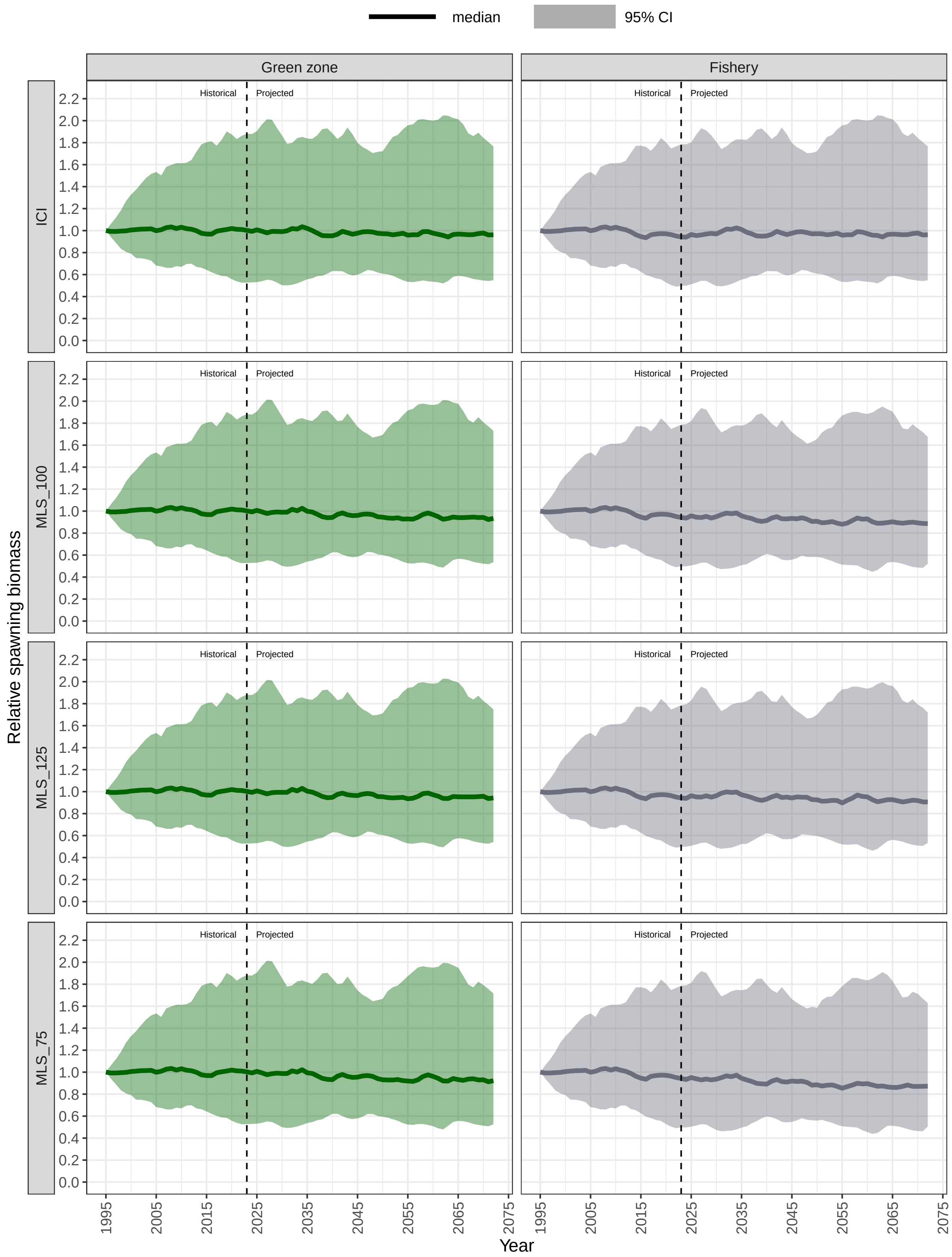

Figure C.24: Leopardfish projected biomass under management procedures without rotational harvest strategy

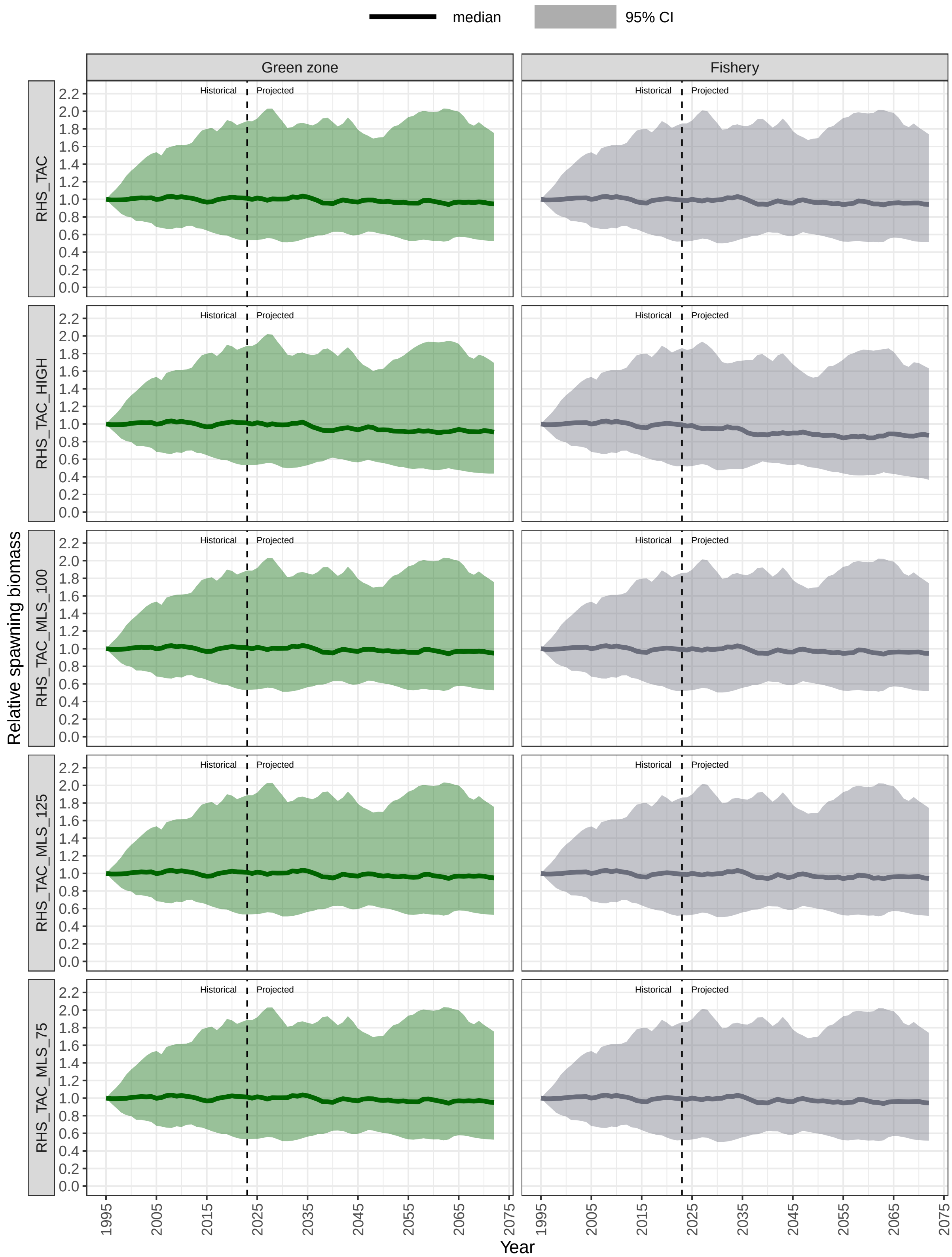

Figure C.25: Leopardfish projected biomass under management procedures with rotational harvest strategy

C.10 Prickly redfish

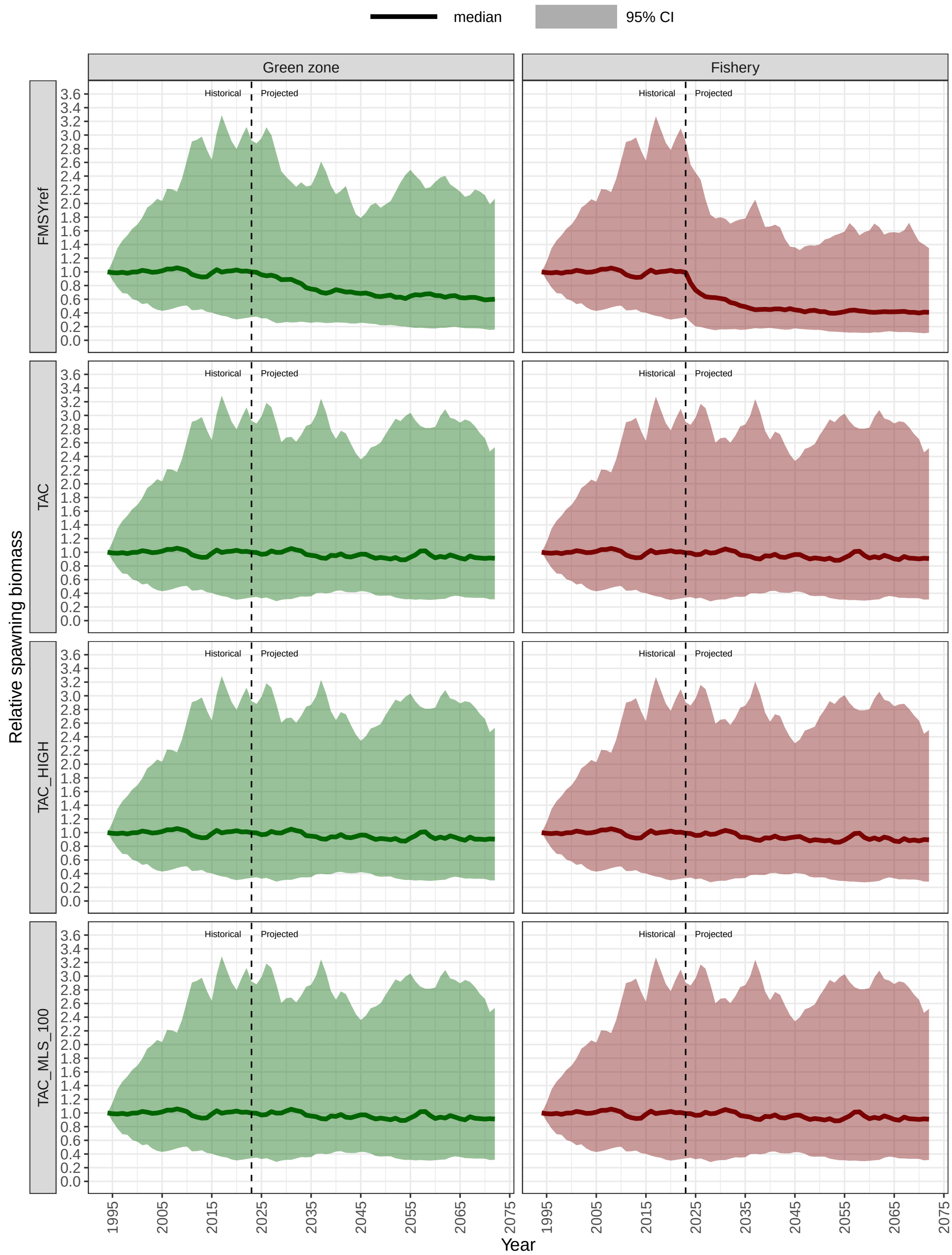

Figure C.26: Prickly redfish projected biomass under management procedures without rotational harvest strategy

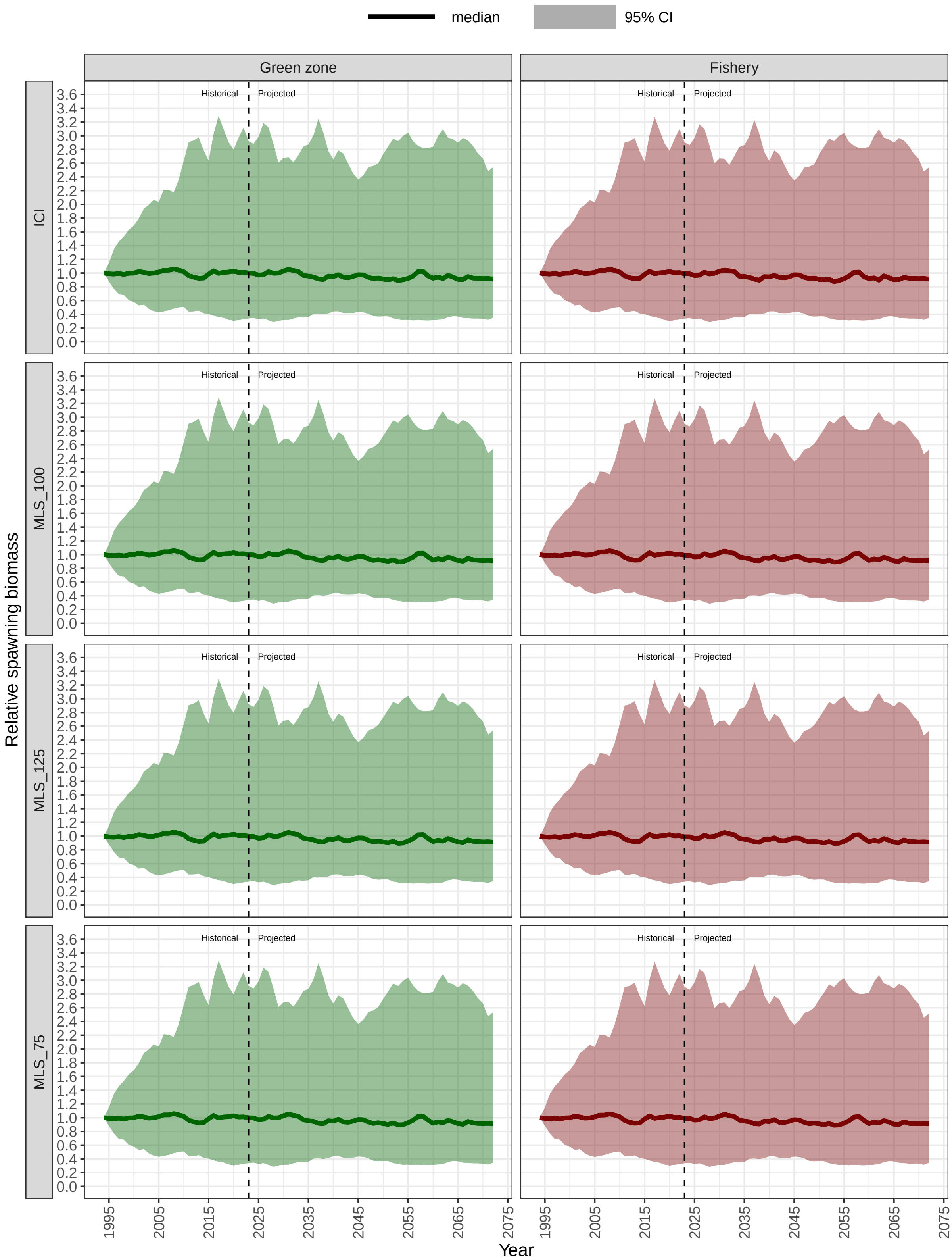

Figure C.27: Prickly redfish projected biomass under management procedures without rotational harvest strategy

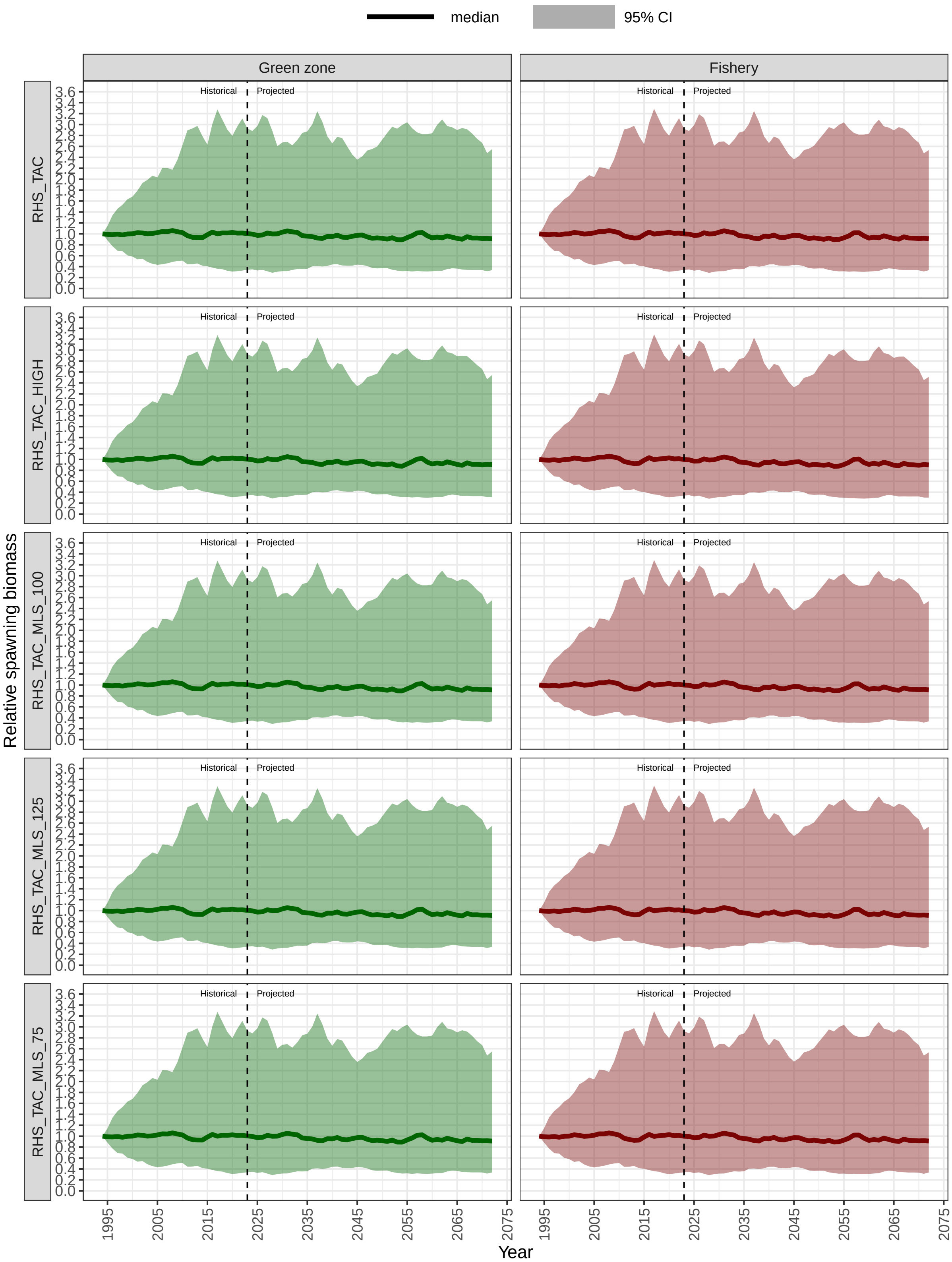

Figure C.28: Prickly redfish projected biomass under management procedures with rotational harvest strategy

C.11 Sandfish

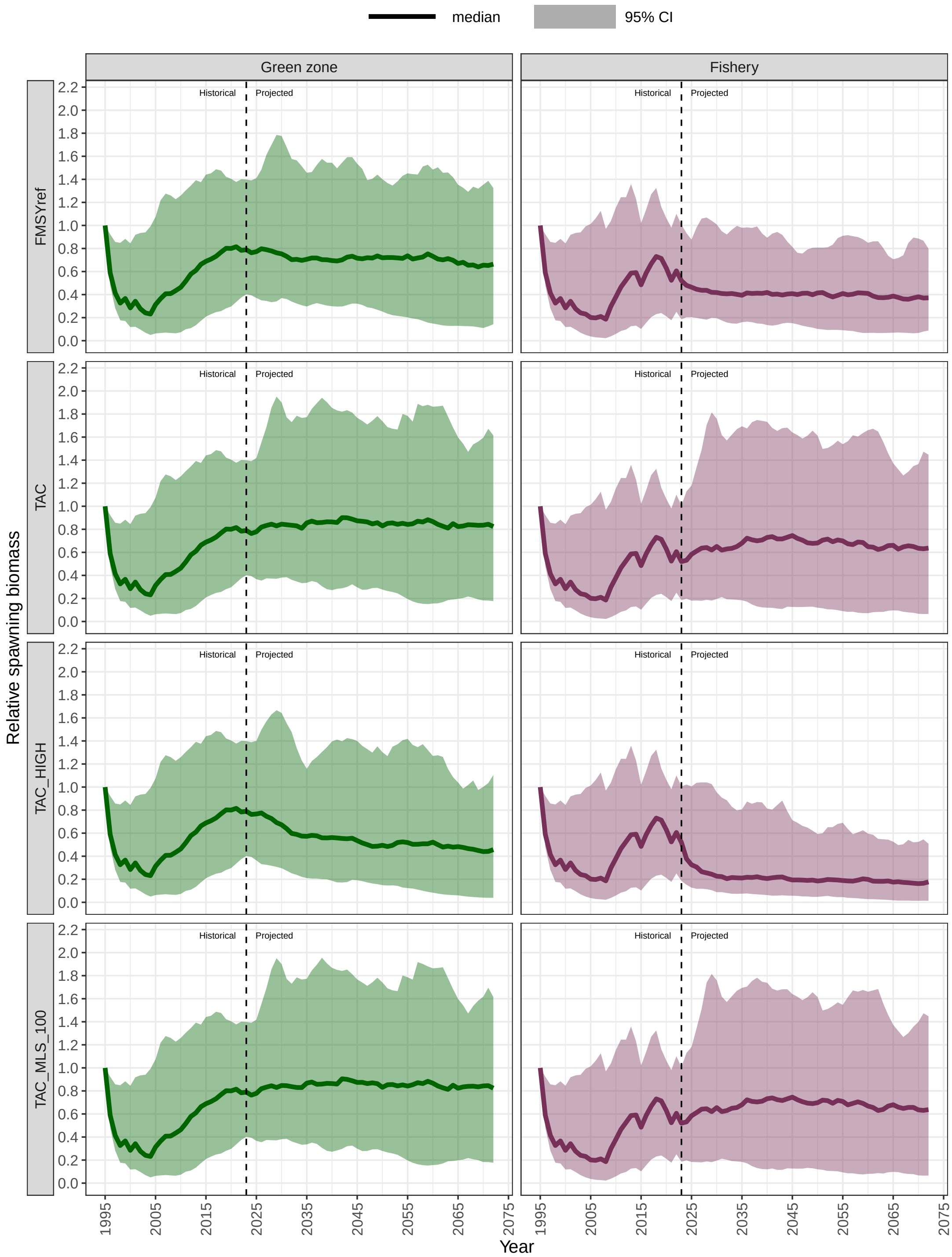

Figure C.29: Sandfish projected biomass under management procedures without rotational harvest strategy

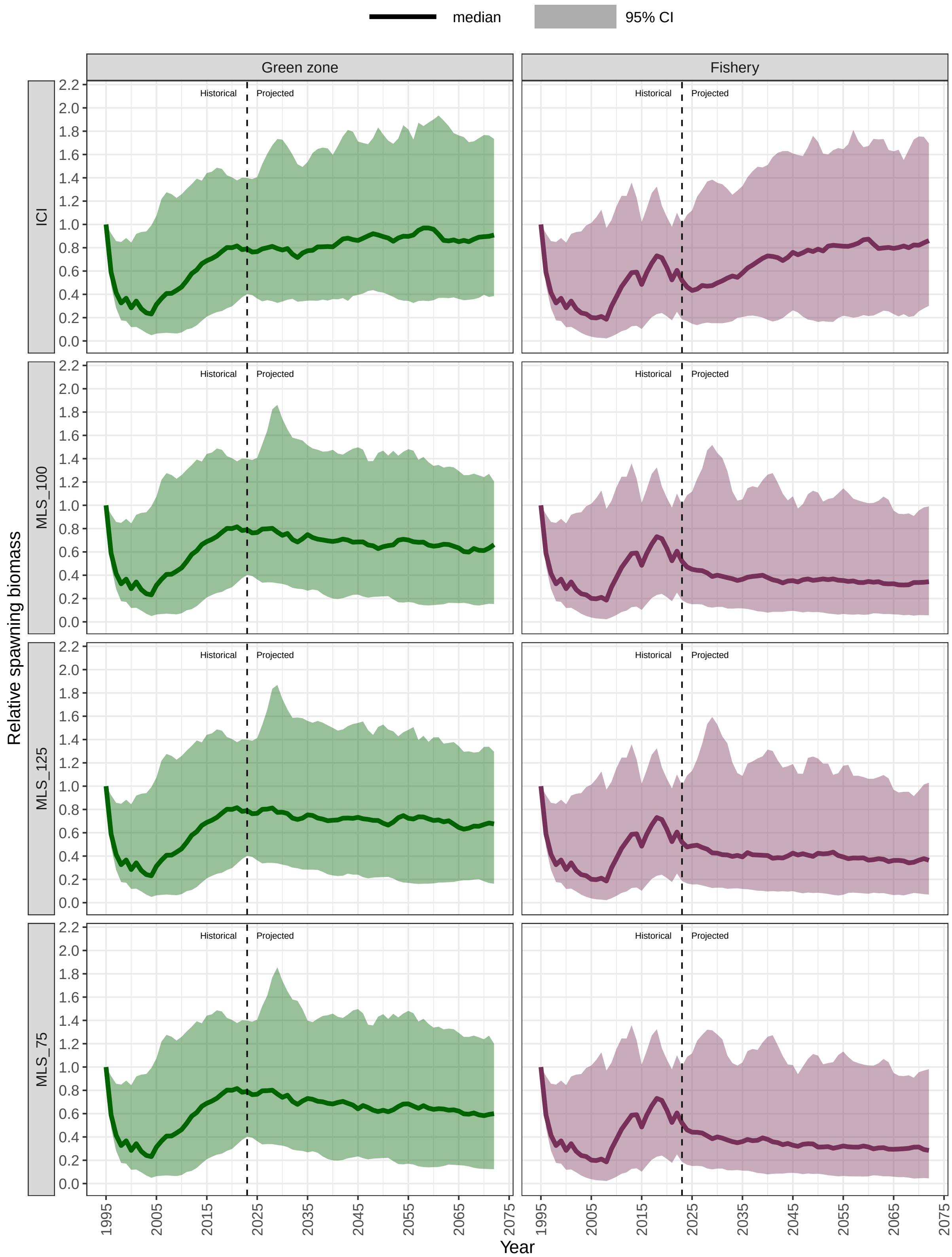

Figure C.30: Sandfish projected biomass under management procedures without rotational harvest strategy

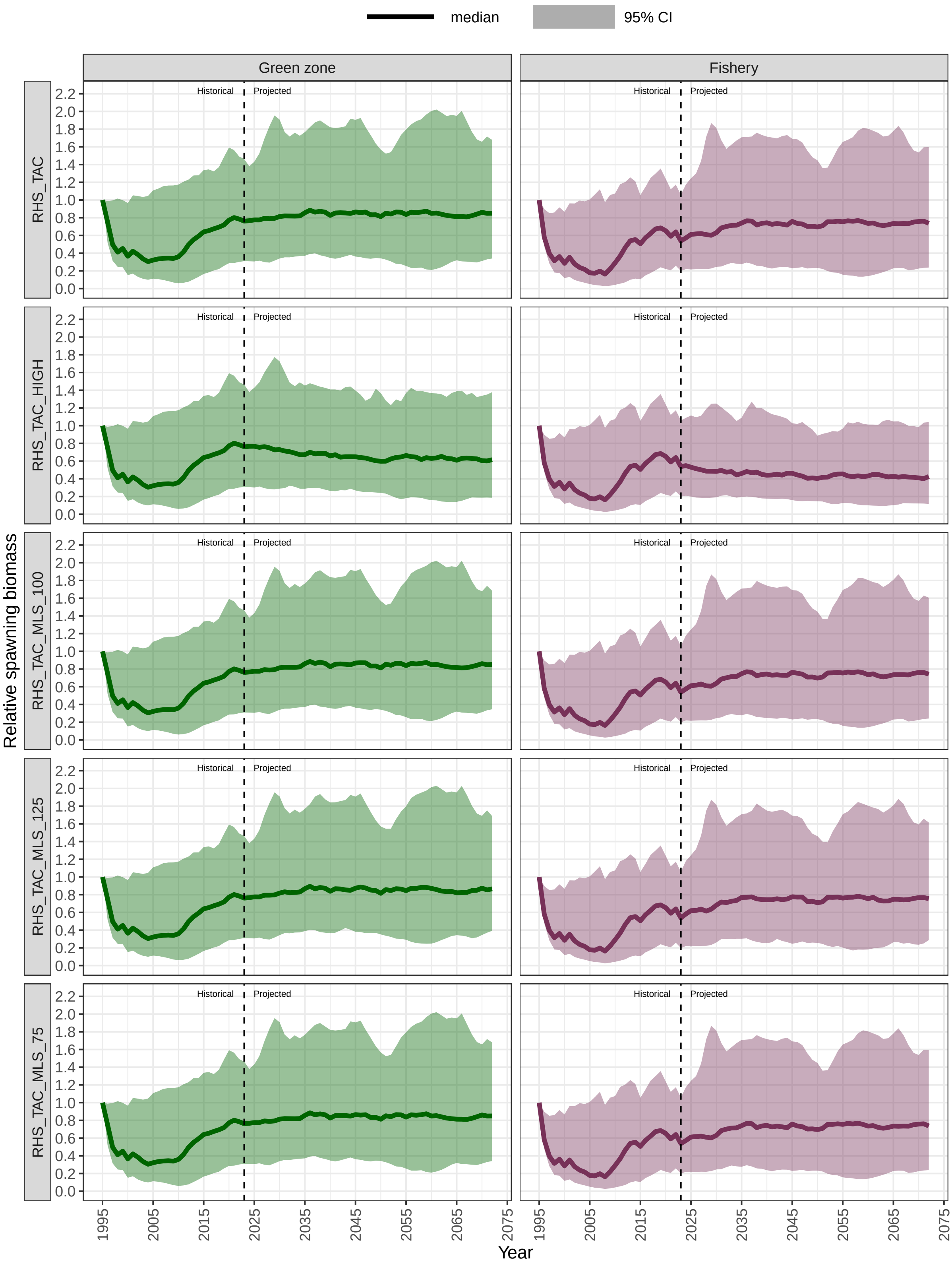

Figure C.31: Sandfish projected biomass under management procedures with rotational harvest strategy

C.12 Vastus curryfish

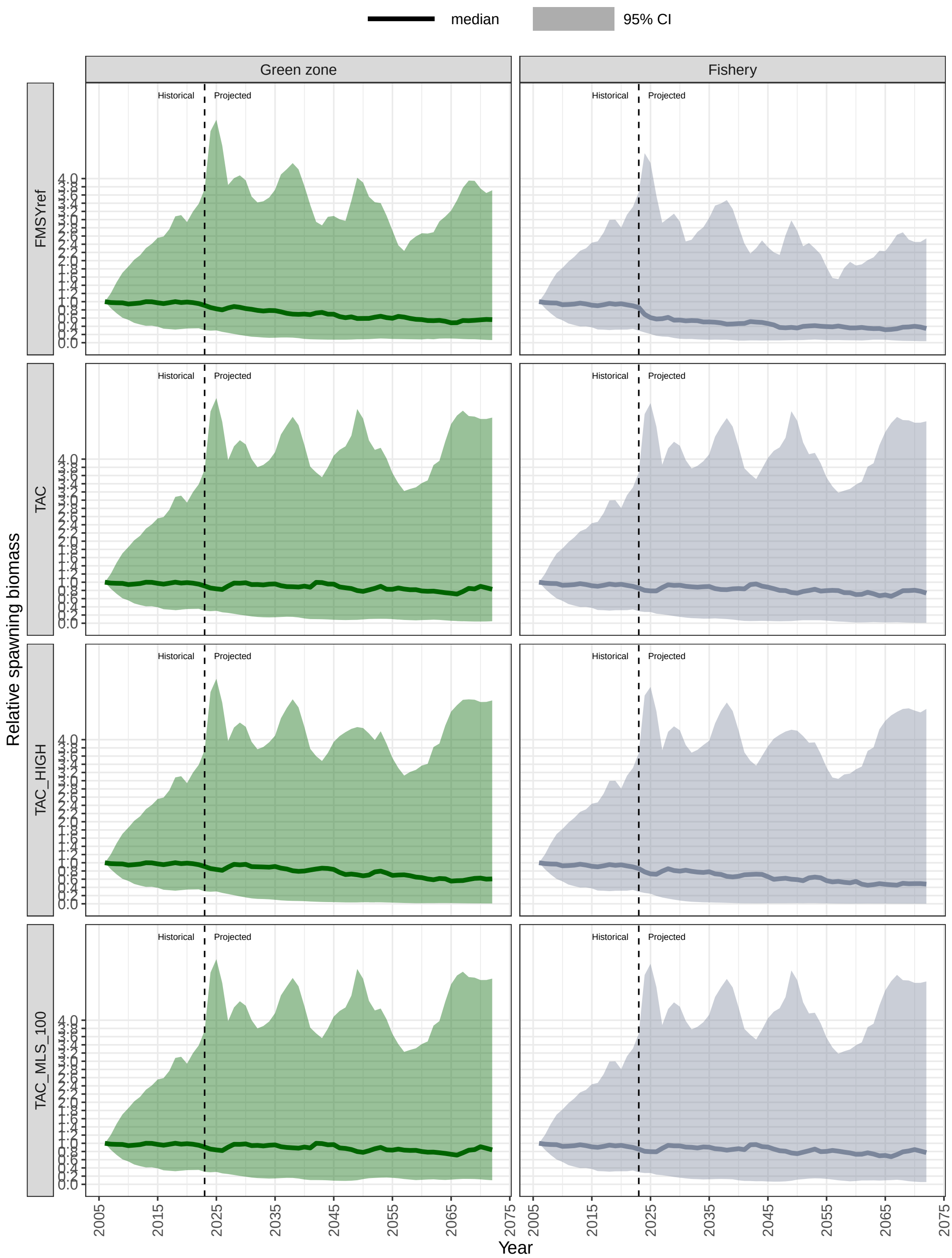

Figure C.32: Vastus curryfish projected biomass under management procedures without rotational harvest strategy

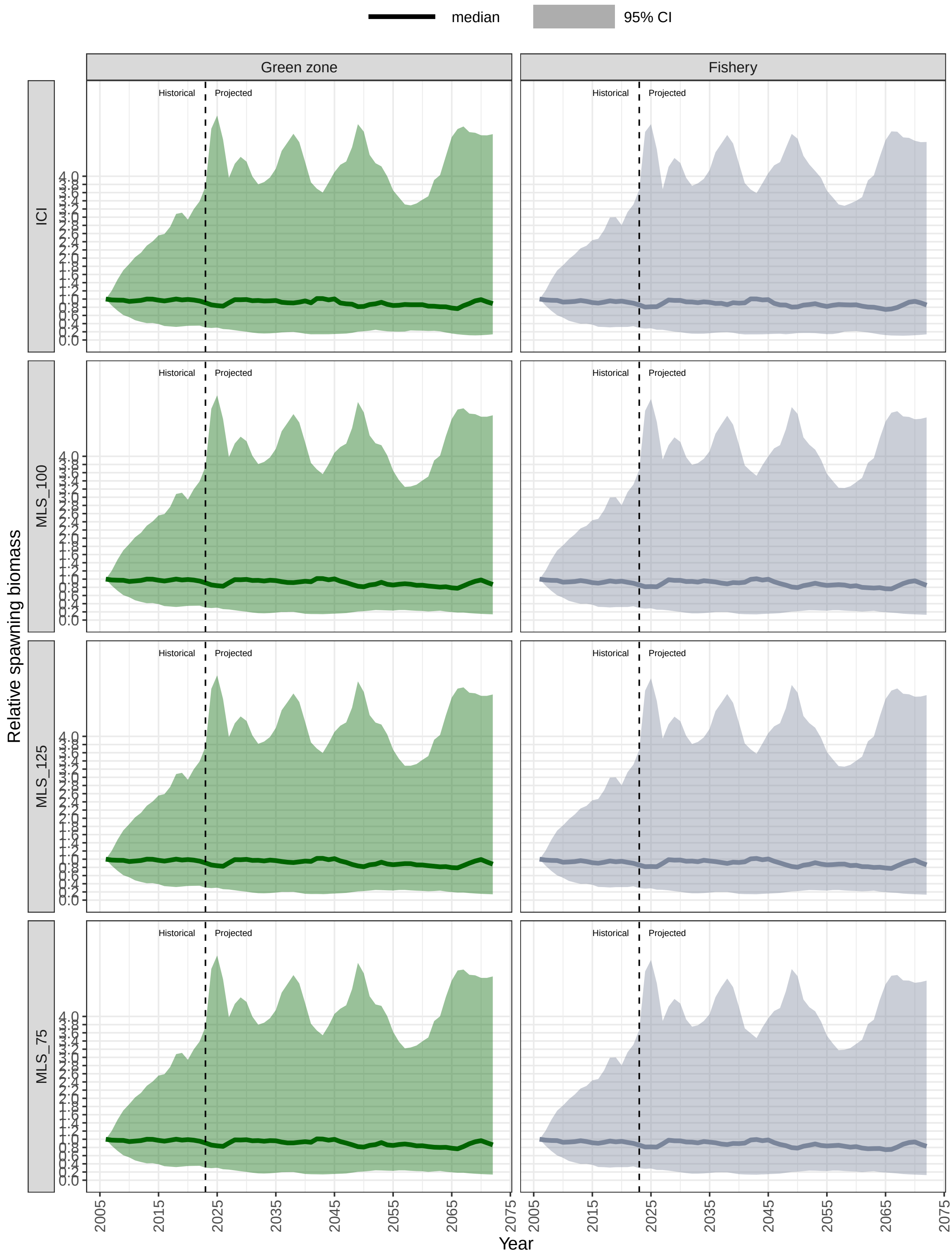

Figure C.33: Vastus curryfish projected biomass under management procedures without rotational harvest strategy

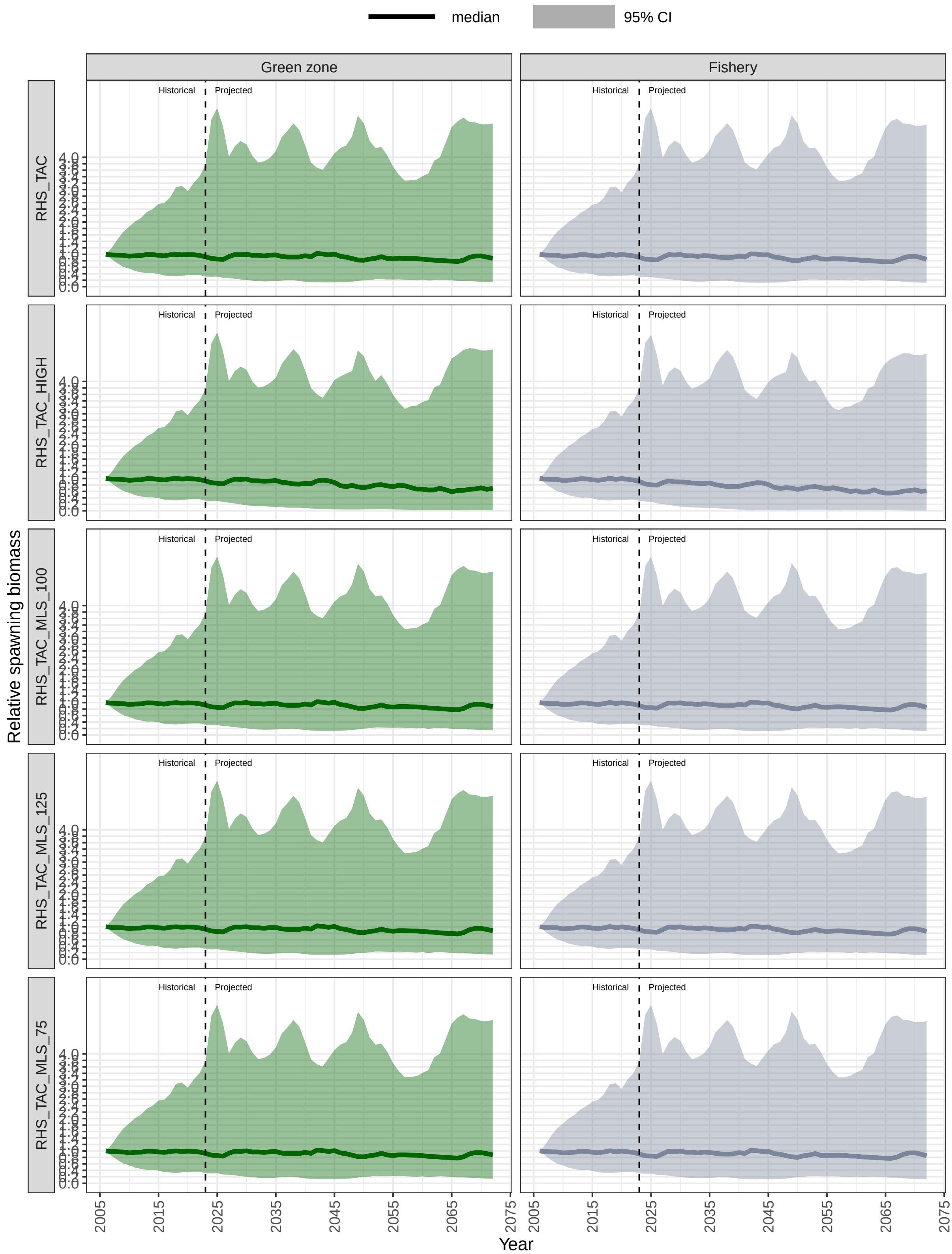

Figure C.34: Vastus curryfish projected biomass under management procedures with rotational harvest strategy

C.13 White teatfish

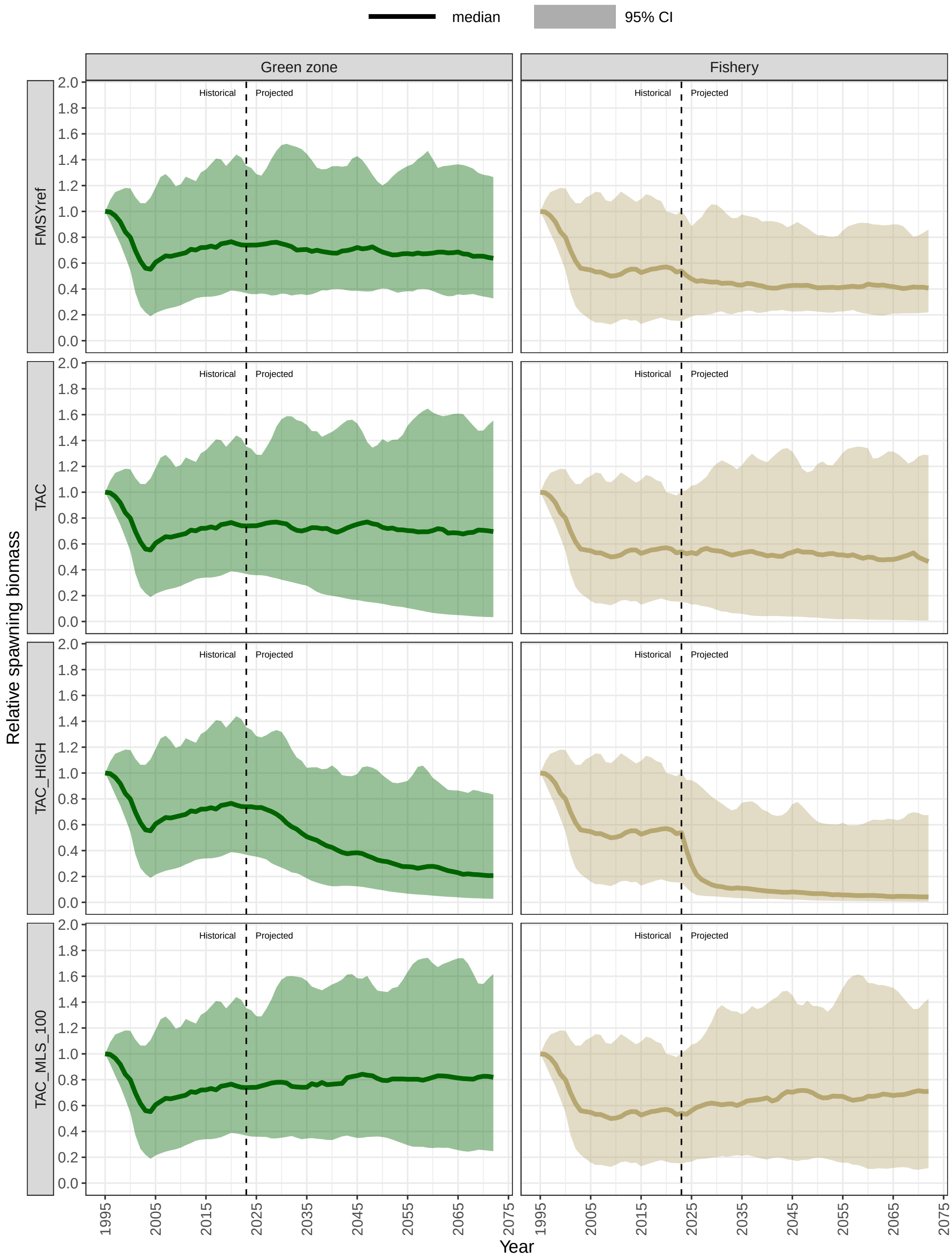

Figure C.35: White teatfish projected biomass under management procedures without rotational harvest strategy

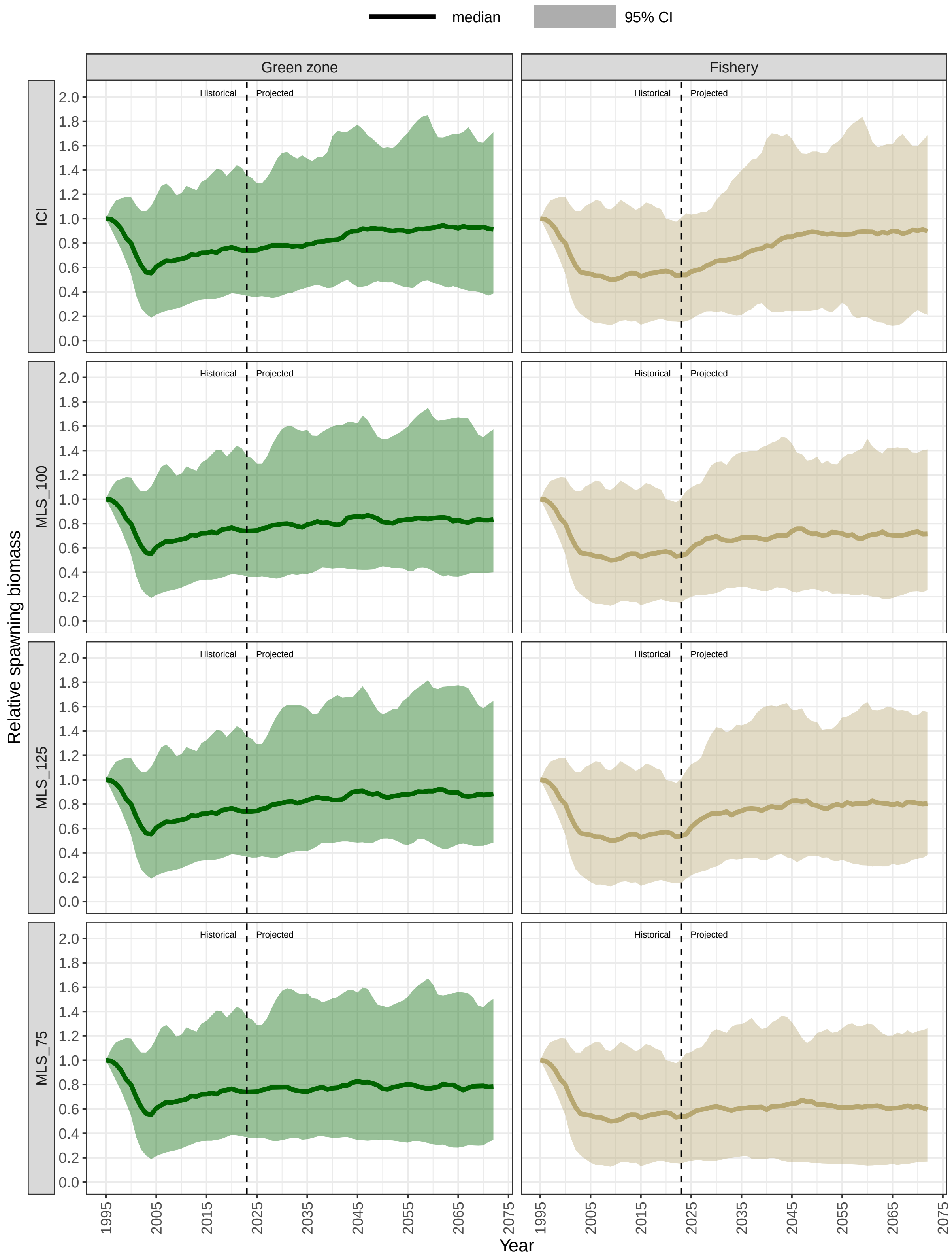

Figure C.36: White teatfish projected biomass under management procedures without rotational harvest strategy

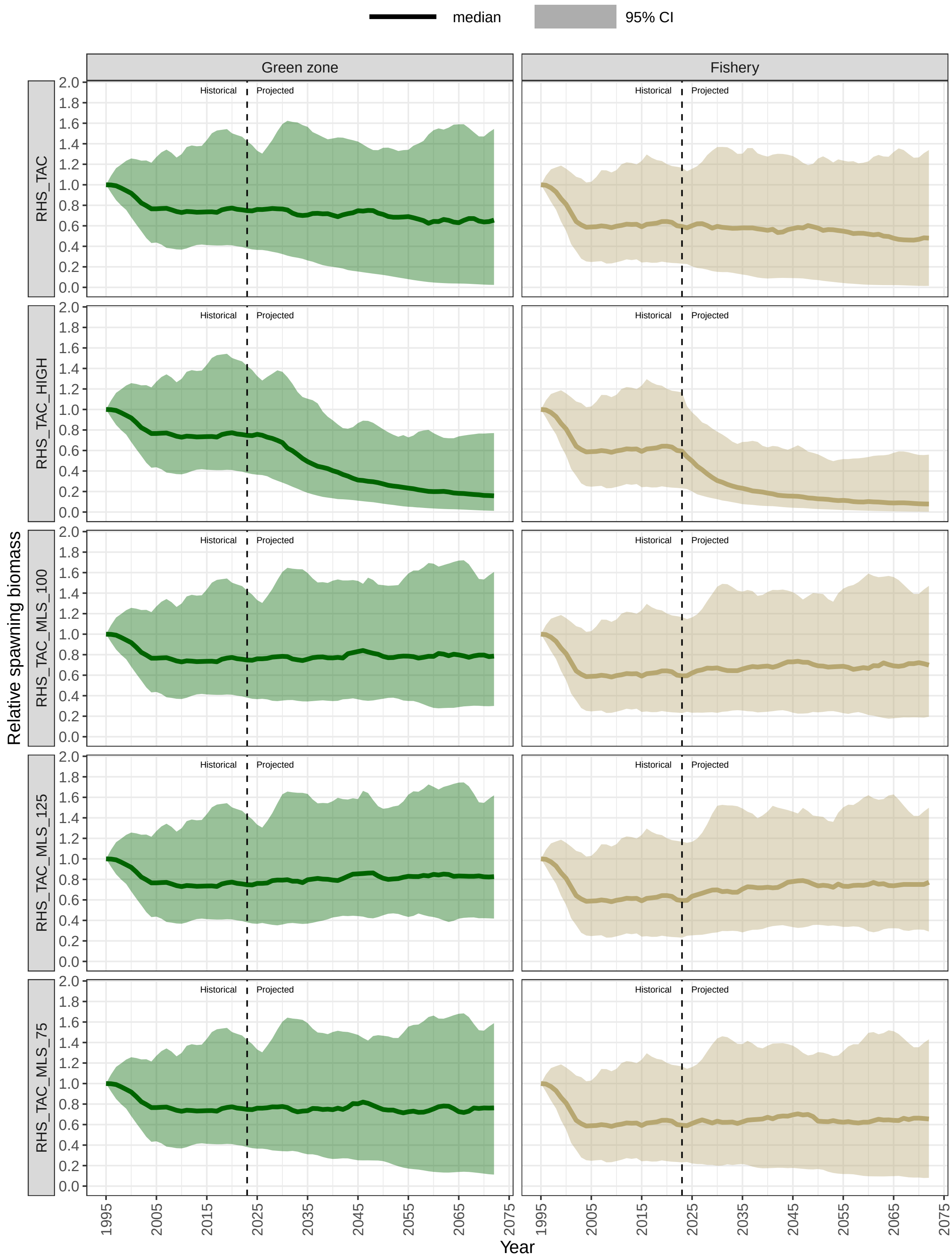

Figure C.37: White teatfish projected biomass under management procedures with rotational harvest strategy

Appendix D Assessment model diagnostics

D.1 Burrowing blackfish (Bunker)

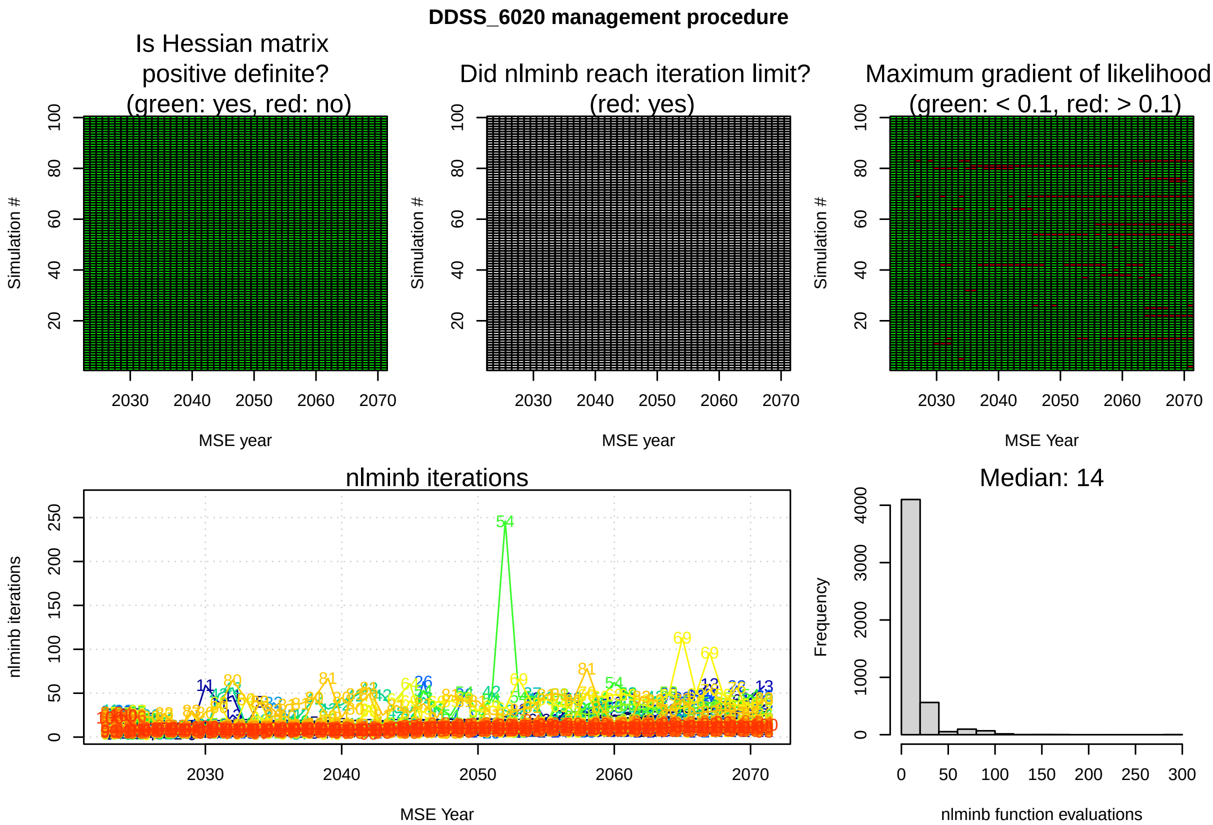

Figure D.1: Burrowing blackfish (Bunker) closed-loop asssessment model diagnostic. Top left plot indicates convergence using the hessian matrix. Top middle plot indicates if optimisation algorithm reached the iteration limit. Top right plot indicates the maximum gradient of final likelihood. Bottom left plot shows the number of iterations for each simulation each year. Bottom right plot shows the number of function evaluations per simulation per year.

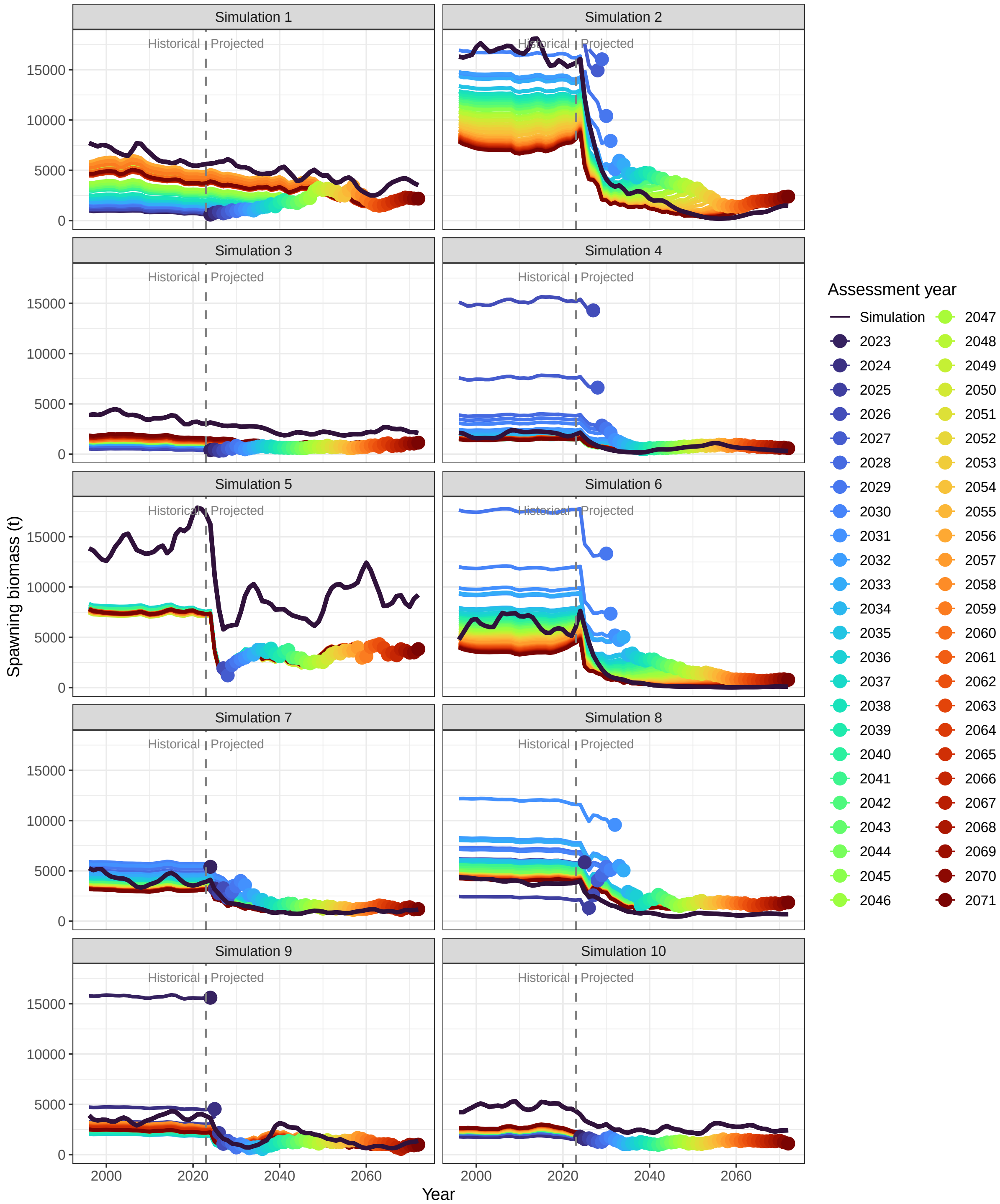

Figure D.2: Burrowing blackfish (Bunker) closed-loop assessment model retrospective for 10 illustrative simulations. The simulated population trajectory is in black and the biomass result from the assessment model each year is in colour.

D.2 Burrowing blackfish (Gould)

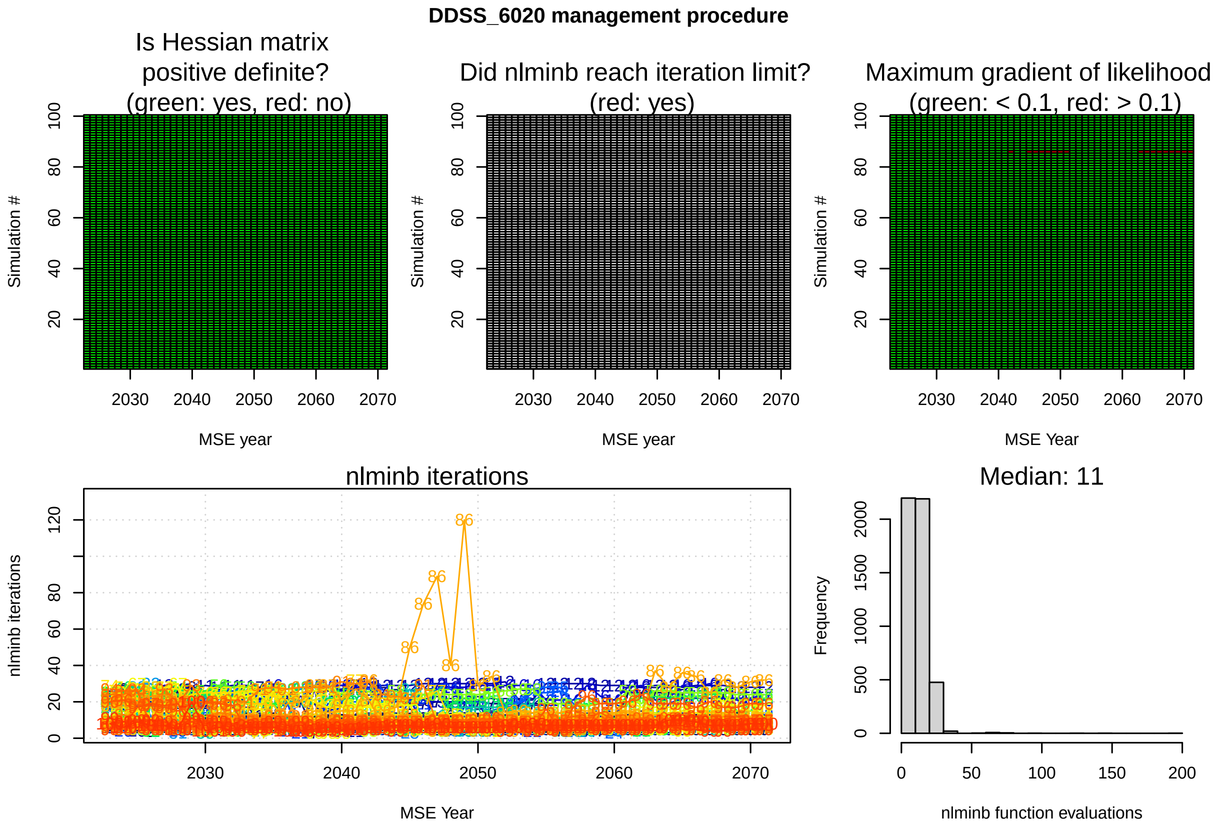

Figure D.3: Burrowing blackfish (Gould) closed-loop asssessment model diagnostic. Top left plot indicates convergence using the hessian matrix. Top middle plot indicates if optimisation algorithm reached the iteration limit. Top right plot indicates the maximum gradient of final likelihood. Bottom left plot shows the number of iterations for each simulation each year. Bottom right plot shows the number of function evaluations per simulation per year.

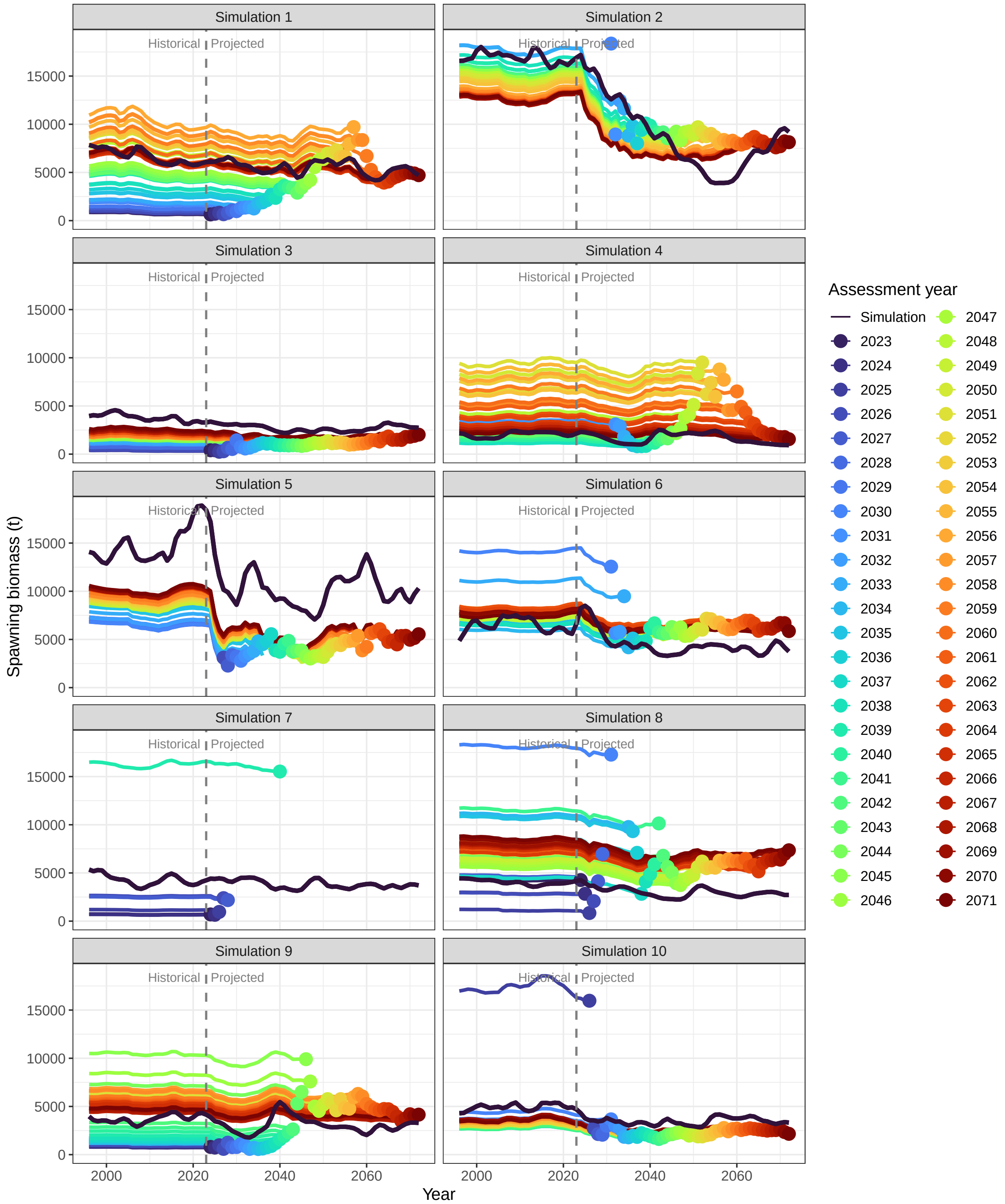

Figure D.4: Burrowing blackfish (Gould) closed-loop assessment model retrospective for 10 illustrative simulations. The simulated population trajectory is in black and the biomass result from the assessment model each year is in colour.

D.3 Herrmanni curryfish

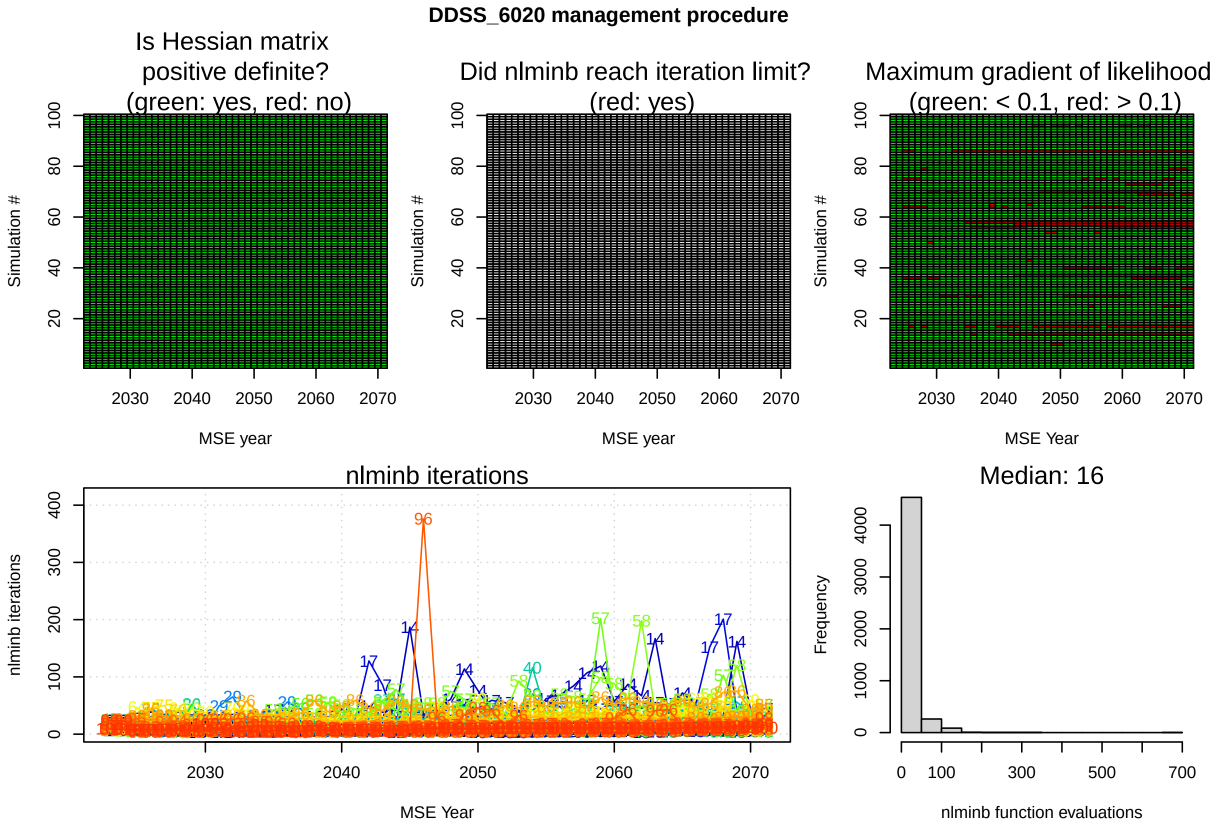

Figure D.5: Herrmanni curryfish closed-loop asssessment model diagnostic. Top left plot indicates convergence using the hessian matrix. Top middle plot indicates if optimisation algorithm reached the iteration limit. Top right plot indicates the maximum gradient of final likelihood. Bottom left plot shows the number of iterations for each simulation each year. Bottom right plot shows the number of function evaluations per simulation per year.

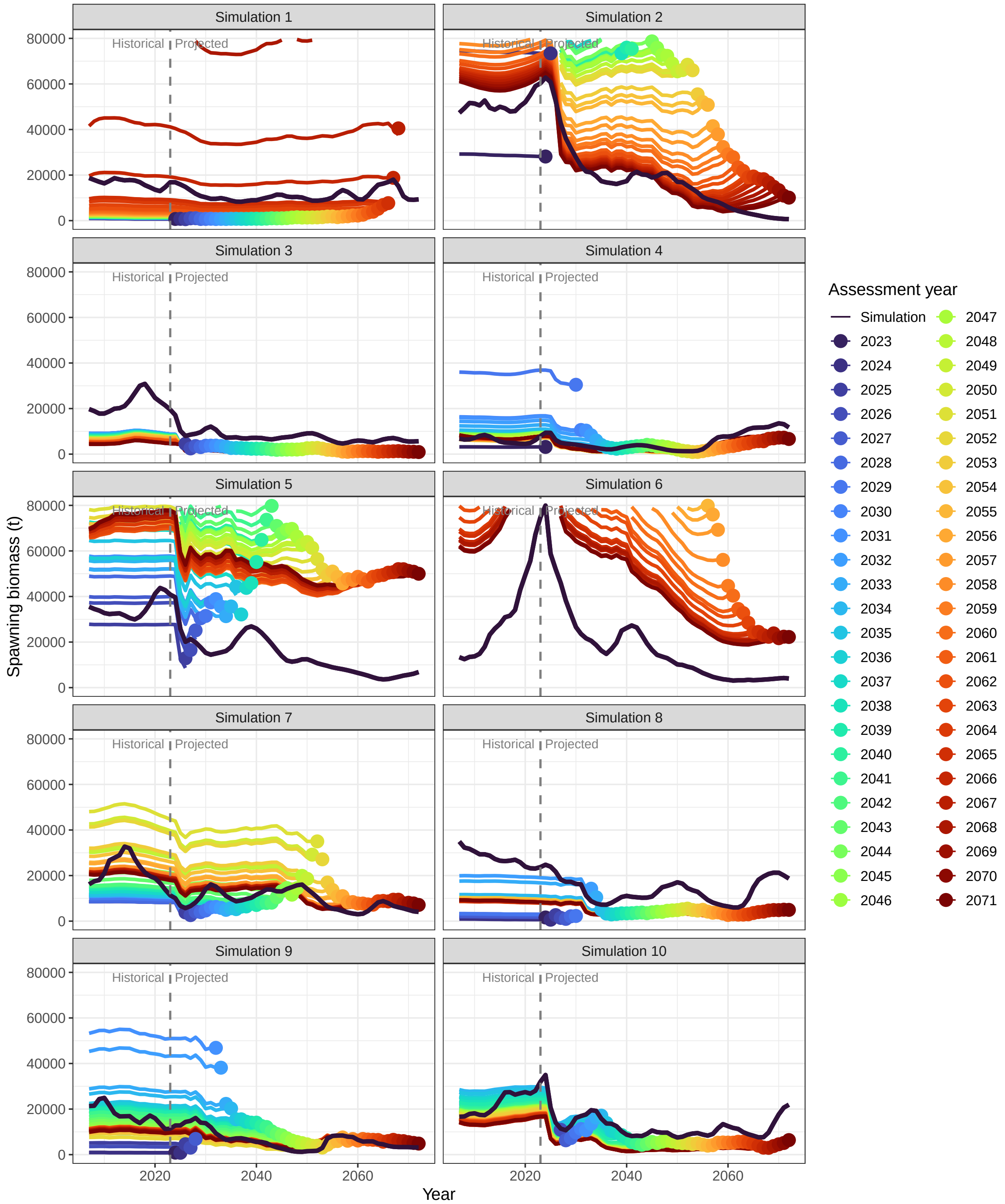

Figure D.6: Herrmanni curryfish closed-loop assessment model retrospective for 10 illustrative simulations. The simulated population trajectory is in black and the biomass result from the assessment model each year is in colour.

D.4 Prickly redfish

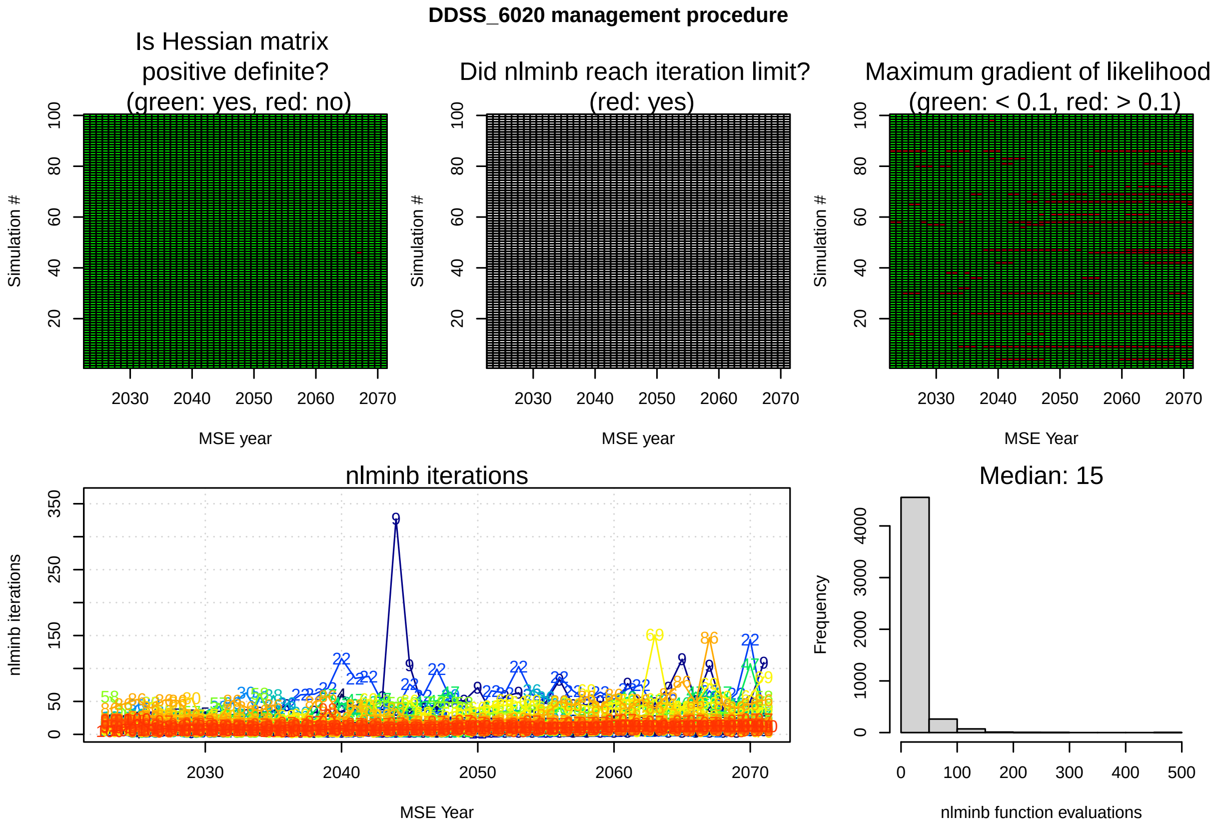

Figure D.7: Prickly redfish closed-loop asssessment model diagnostic. Top left plot indicates convergence using the hessian matrix. Top middle plot indicates if optimisation algorithm reached the iteration limit. Top right plot indicates the maximum gradient of final likelihood. Bottom left plot shows the number of iterations for each simulation each year. Bottom right plot shows the number of function evaluations per simulation per year.

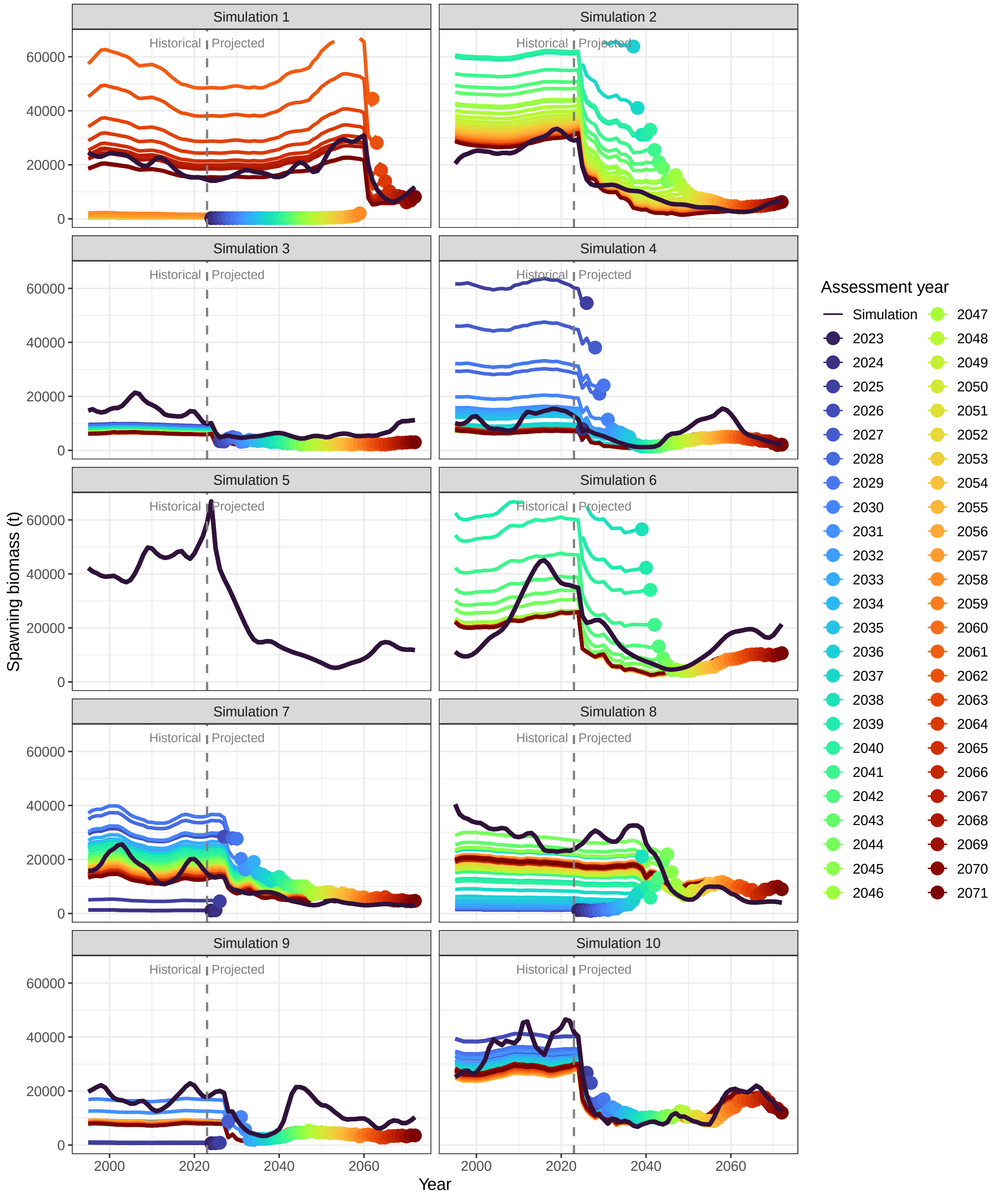

Figure D.8: Prickly redfish closed-loop assessment model retrospective for 10 illustrative simulations. The simulated population trajectory is in black and the biomass result from the assessment model each year is in colour.

D.5 Vastus curryfish

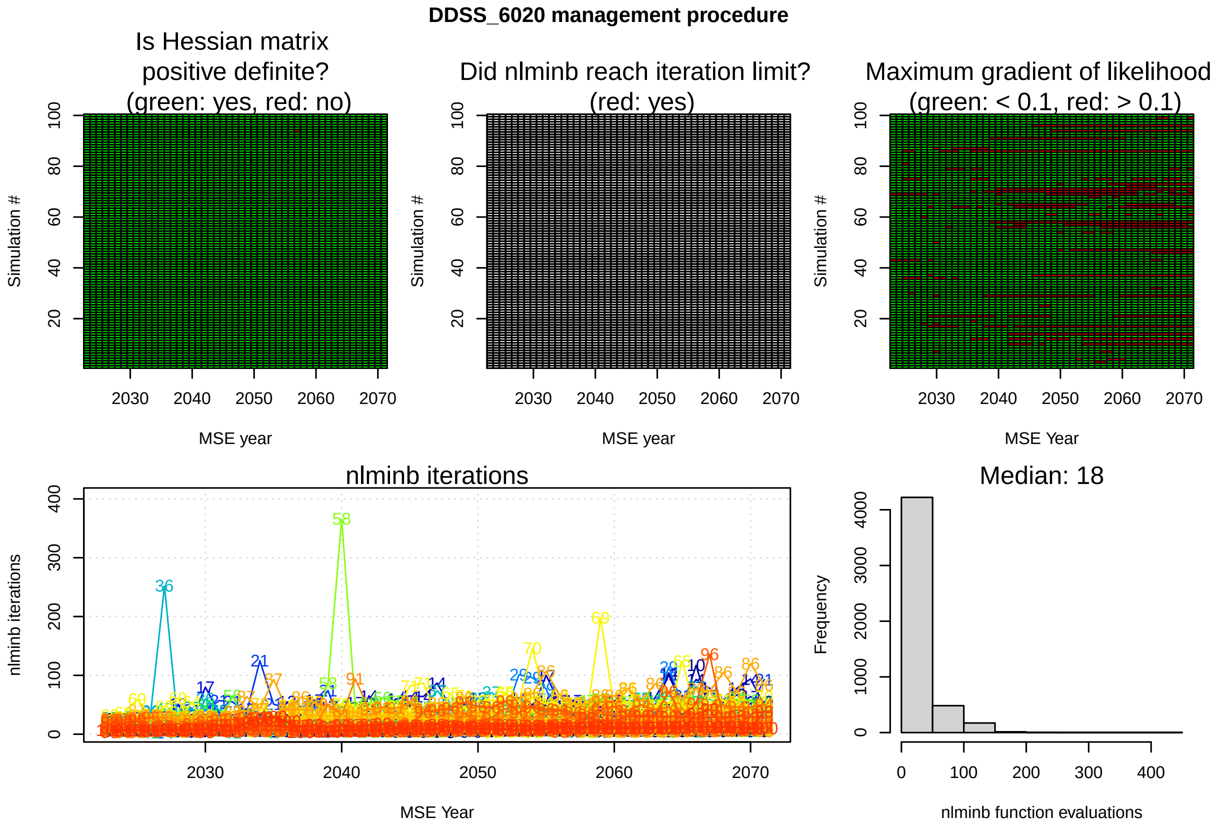

Figure D.9: Vastus curryfish closed-loop asssessment model diagnostic. Top left plot indicates convergence using the hessian matrix. Top middle plot indicates if optimisation algorithm reached the iteration limit. Top right plot indicates the maximum gradient of final likelihood. Bottom left plot shows the number of iterations for each simulation each year. Bottom right plot shows the number of function evaluations per simulation per year.

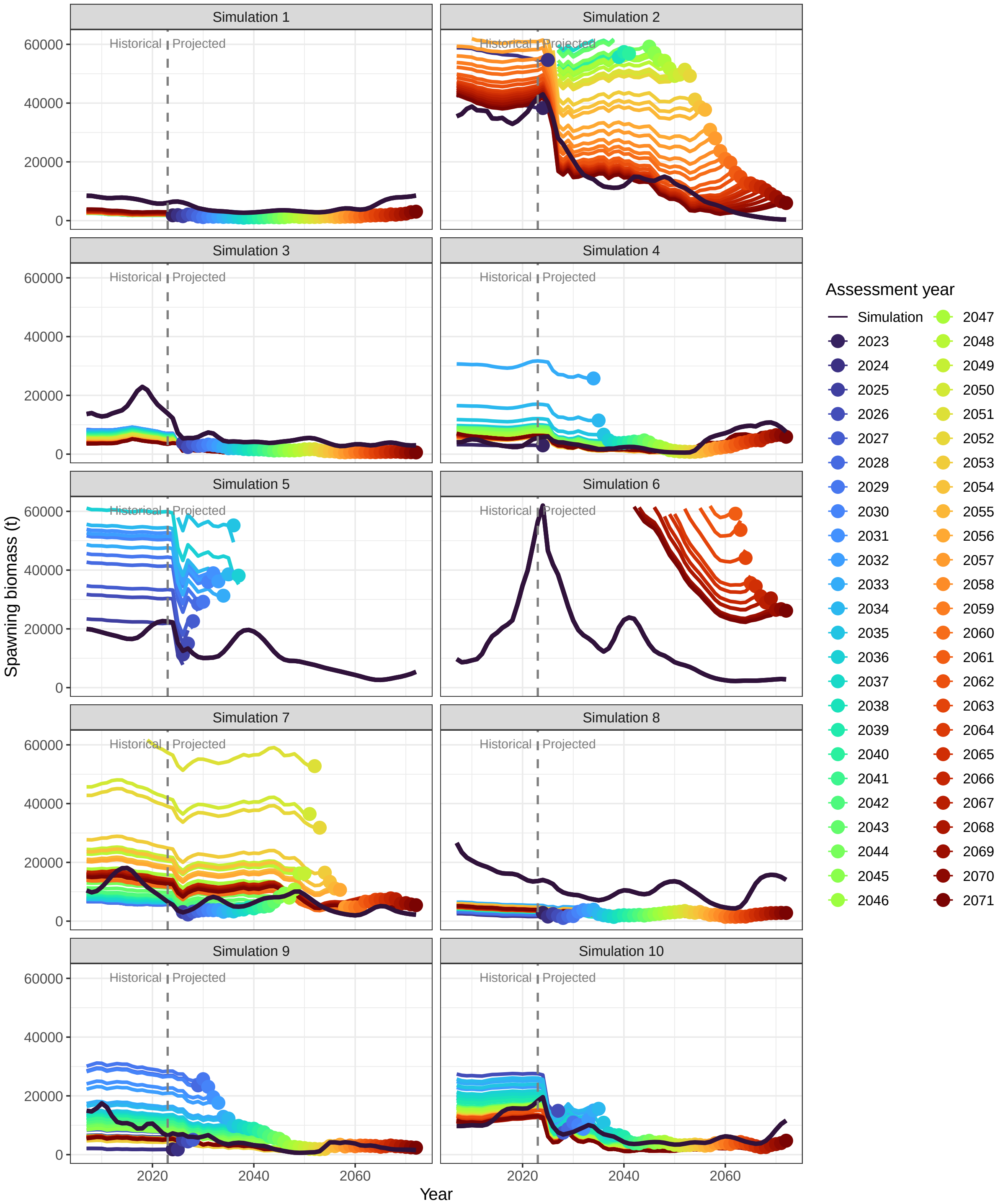

Figure D.10: Vastus curryfish closed-loop assessment model retrospective for 10 illustrative simulations. The simulated population trajectory is in black and the biomass result from the assessment model each year is in colour.