Fisheries New Zealand

Tini a Tangaroa

Harvest control rule evaluations for southern blue whiting (*Micromesistius australis*) on the Campell Island Rise for the 2023–24 fishing year

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Table of Contents

EXECUTIVE SUMMARY

Dunn, A.[1] **(2024). Harvest control rule evaluations for southern blue whiting (*Micromesistius australis*) on the Campell Island Rise for the 2023–24 fishing year.**

***New Zealand Fisheries Assessment Report 2024/xx*. 30 p.**

Management Procedures (MP, also known as Management Strategies) provide a framework for determining an appropriate fisheries management regime that can account for a wide range of biological and fisheries management uncertainties. This work focuses on known and major uncertainties for southern blue whiting on the Campbell Island Rise (SBW 6I), specifically by including uncertainties in recruitment and those due to delays in the management response (from assessment to TACC setting). The MP simulates the dynamics of a stock under different catch scenarios specified by candidate Harvest Control Rules (HCRs). The performance of the individual HCRs is evaluated using a set of performance indicators (PIs) that include measures of sustainability and utilisation, and hence are evaluated for their ability to meet the management objectives

This report provides HCR evaluations for the SBW 6I using the most recent stock assessments. The assessment was based using data up to the end of the 2022–23 fishing year, and the indices of abundance were the Campbell Island Rise *Tangaroa* acoustic survey series along with fishery and survey age composition data.

The MPs evaluate sets of candidate HCRs that define a target biomass range, and corresponding levels of catch based on a proxy of the assessment for spawning stock biomass. The HCRs set the catches at a level when the stock was assessed and are aimed at moving the biomass towards the target biomass. Annual catches were decreased when the stock was below the target biomass or increased when the stock was above the target biomass. The HCRs assumed future recruitments for stocks would be at levels comparable to the recruitment estimated in the stock assessment model.

Estimates from the HCRs suggested a target biomass range of 40–55% B_0 would maintain the stock above the sustainability threshold of 20% B_0 with a probability of at least 90%, and the stock would fluctuate at a level of at least 40% B_0. The annual catches evaluated by the HCRs suggest the stock yielded average annual catches of between 20 000–30 000 t for SBW 6I, assuming future recruitment at the average historical levels. However, there was considerable variability in annual catches between years, primarily in response to variability in annual recruitments, and the HCRs assume three-yearly changes in catch limits that are required to maintain the stock within the target biomass range.

The robustness of the HCRs will depend on the assumptions of the assessment model, particularly the assumption that future recruitment will continue to be at a level similar to that estimated for the historical period (the 10-year recent recruitments have been slightly above average) in the assessment model, that surveys are conducted at three-year intervals with associated age composition data, and annual fishery age compositions are available. Implementation of specific HCRs would also require the specification of a set of break-out rules for managing the stock beyond the scope of the current operating model, for example, in response to a sustained period of recruitment different from that assumed in the MP evaluation or if the triennial surveys were not conducted.

[1] Ocean Environmental Ltd., Wellington, New Zealand.

1. INTRODUCTION

Southern blue whiting (*Merluccius australis*) is an important commercially caught species restricted in distribution to sub-Antarctic waters. They are caught over the Campbell Plateau and Bounty Plateau for much of the year, and during August and September they aggregate for spawning on the Campbell Island Rise, Pukaki Rise, Bounty Plateau, and around the Auckland Islands. SBW are typically found in depths of from 250 to 600 m and almost all catch is from direct targeting by trawlers on aggregations at or around spawning.

The current management of southern blue whiting divides the fishery into five Fishstocks (Figure 1): (i) Bounty Planform (SBW 6B), Pukaki Rise (SBW 6R), the Campbell Island Rise (SBW 6I), the Auckland Islands (SBW 6A), and the remainder of the New Zealand EEZ (SBW 1) (Fisheries New Zealand 2023). There are likely to be four main biological stocks of southern blue whiting with each area other than SBW 1 representing a separate stock (Fisheries New Zealand 2023).

Southern blue whiting stocks have previously been assessed with stock assessments since 1991. The most recent assessment of southern blue whiting on the Campbell Island Rise was for the 2022–23 fishing year (Doonan et al. 2024) The next assessment is scheduled for 2025–26 (Fisheries New Zealand 2022).

Doonan et al. (2024) updated the southern blue whiting assessment for SBW 6I using commercial age composition data, and acoustic survey biomass indices and age composition observations including available data up to the end of the 2022 fishing year, and using the Bayesian stock assessment software Casal2 (Casal2 Development Team 2022). The assessment concluded that the spawning stock status for 2021 was about 63% B_0 (95% credible intervals 47–82% B_0) after a period of lower than allowed catches and stronger than average recruitment. Acoustic survey biomass indices were available from 1993 to 2022 and are currently undertaken at three-year intervals, with the next scheduled for 2025.

The development of Management Procedures (MP, also known as Management Strategy Evaluations) (Butterworth & Punt 1999, Butterworth 2007) for southern blue whiting was to determine an appropriate management regime for these fisheries, taking into account the uncertainty in the assessment model assumptions, recent recruitments and time lag in management responses. In the Medium-Term Research Plan for Deepwater Fisheries (Fisheries New Zealand 2020), Fisheries New Zealand noted that there was an intention to run MSE for Tier 1 stocks wherever possible.

The MP method simulates the dynamics of each of the stocks and associated fisheries under different catch scenarios specified by candidate Harvest Control Rules (HCRs). The performance of the individual HCRs is evaluated based on a set of performance indicators (PIs) based on the sustainability, utilisation, and economic objectives. The trade-offs between performance can be used to identify an optimal HCR and hence provide information on the likely level of yields available and the appropriate management responses required to maintain the stock at a level that meets the management objectives.

MPs have been previously conducted for the southern blue whiting stock on the Campbell Island Rise by Cordue (2015). This report provides an evaluation of a set of candidate MPs for Campbell Island Rise southern blue whiting, based on the methods developed by Dunn (2024). This report was funded by the Seafood New Zealand Deepwater Council, with the specific objectives “to develop a Management Strategy Evaluation for southern blue whiting to determine an appropriate management regime for these fisheries, taking into account the uncertainty in the assessment model assumptions, recent recruitments and delay in management responses”.

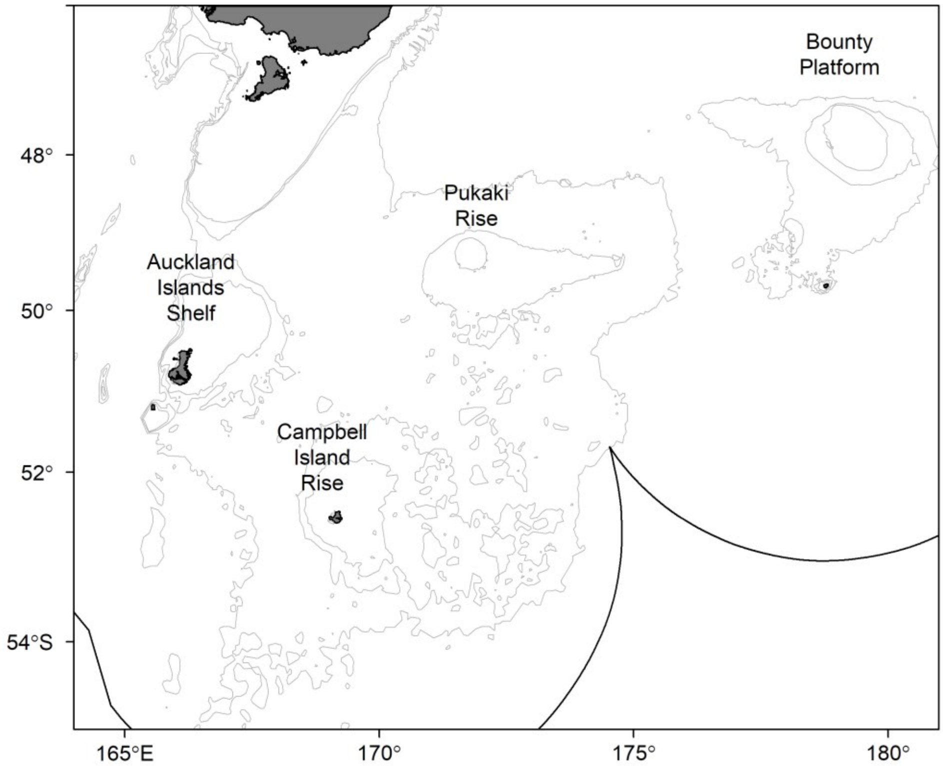

Figure 1: Southern New Zealand and the southern blue whiting management regions (Bounty Platform, Pukaki Rise, Campbell Island Ruise, and the Auckland Islands. Depth contours (grey) are shown for 1000 m, 500 m, and 250 m).

2. METHODS

2.1 Management objectives

The MPs were based on an operating model using the most recent stock assessment for SBW 6 I ((Doonan et al. 2024) each area and the MPs were undertaken using the same methods as Dunn (2024). The assessment model assumed the Campbell Island Rise was a single stock, with the model implemented in implemented in Casal2 v22.10 (Casal2 Development Team 2022). For the MPs, the assessment models were updated and rerun in the most recent version of Casal2 (Casal2 Development Team 2024a) and the MPs were then implemented, with pre- and post-processing in R (R Core Team 2022) using the R-libraries *Casal2* (Casal2 Development Team 2024b) and *r4Casal2* (Marsh & Dunn 2024).

The approach used to undertake the MPs was based on that developed for hoki by Langley (2023) and described in detail in Dunn (2024). For each stock, operating models based on the most recent assessments were used to generate simulated values of SSB (as a proxy biomass index). These simulated observations were then used to apply a pre-set decision rule (i.e., an HCR) that updates the catch in the immediate future years. Performance indicators were used to evaluate the HCRs under these different scenarios. The general approach to MPs is given in Figure 1 and the MP is described in more detail below.

The Fisheries New Zealand Annual Operational Plan for Deepwater Fisheries (AOPDF) 2022/23 (Fisheries New Zealand 2022) categorises southern blue whiting as a Tier 1 species, which are high volume or high value fisheries and are usually targeted. They are considered important earners of export revenue, which is reflected in the high quota value associated with these species. The AOPDF defines the *Use Outcome* for southern blue whiting as “Fisheries resources are used in a manner that provides the greatest overall economic, social, and cultural benefit”, with the overall management objectives:

1. Ensure the deepwater and middle-depth fisheries resources are managed so as to provide for the needs of future generations.
2. Ensure excellence in the management of New Zealand's deepwater and middle-depth fisheries, so they are consistent with, or exceed, international best practice.
3. Ensure effective management of the deepwater and middle-depth fisheries is achieved through the availability of appropriate, accurate and robust information.
4. Ensure deepwater and middle-depth fish stocks and key bycatch fish stocks are managed to an agreed harvest strategy or reference points.

For the evaluation of MPs, the conceptual management objectives for the stock were determined in consultation with Fisheries New Zealand Deepwater Fisheries managers, and the Deepwater Council of Seafood New Zealand. The conceptual management objectives defined for the southern blue whiting stocks were:

1. Sustainability objectives
   - i. Maintain the stock at or about the biomass that supports MSY using a proxy of 40% B_0, the target reference point (TRP).
   - ii. Avoid the probability of the stock being below the soft limit reference point (20% B_0, SLRP).
   - iii. Avoid, with high probability, the stock being below the hard limit reference point (10% B_0, HLRP).
2. Utilisation objectives
   - i. Maximise the total average catch over the long term.
3. Economic objectives
   - i. Maximise catch rates (CPUE).
   - ii. Minimise interannual fluctuations to the TACC while not adversely impacting maximising the total average catch.

The approach to the development of the candidate HCRs was also informed by the Marine Stewardship Council (MSC) Fisheries Standard (Marine Stewardship Council 2022) under the Stock status Performance Indicators (Figure 3).

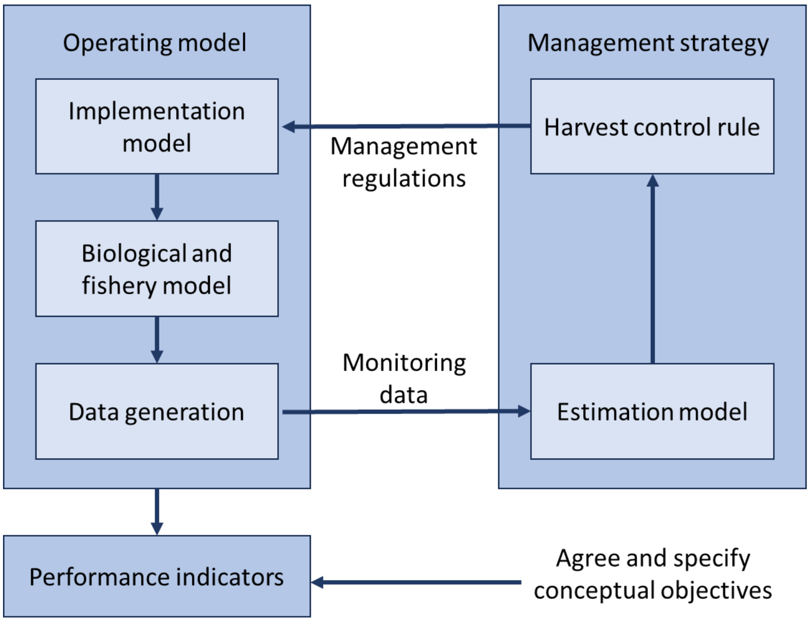

Figure 2: Conceptual overview of the management strategy evaluation modelling process (Figure 1 in Punt et al. 2016).

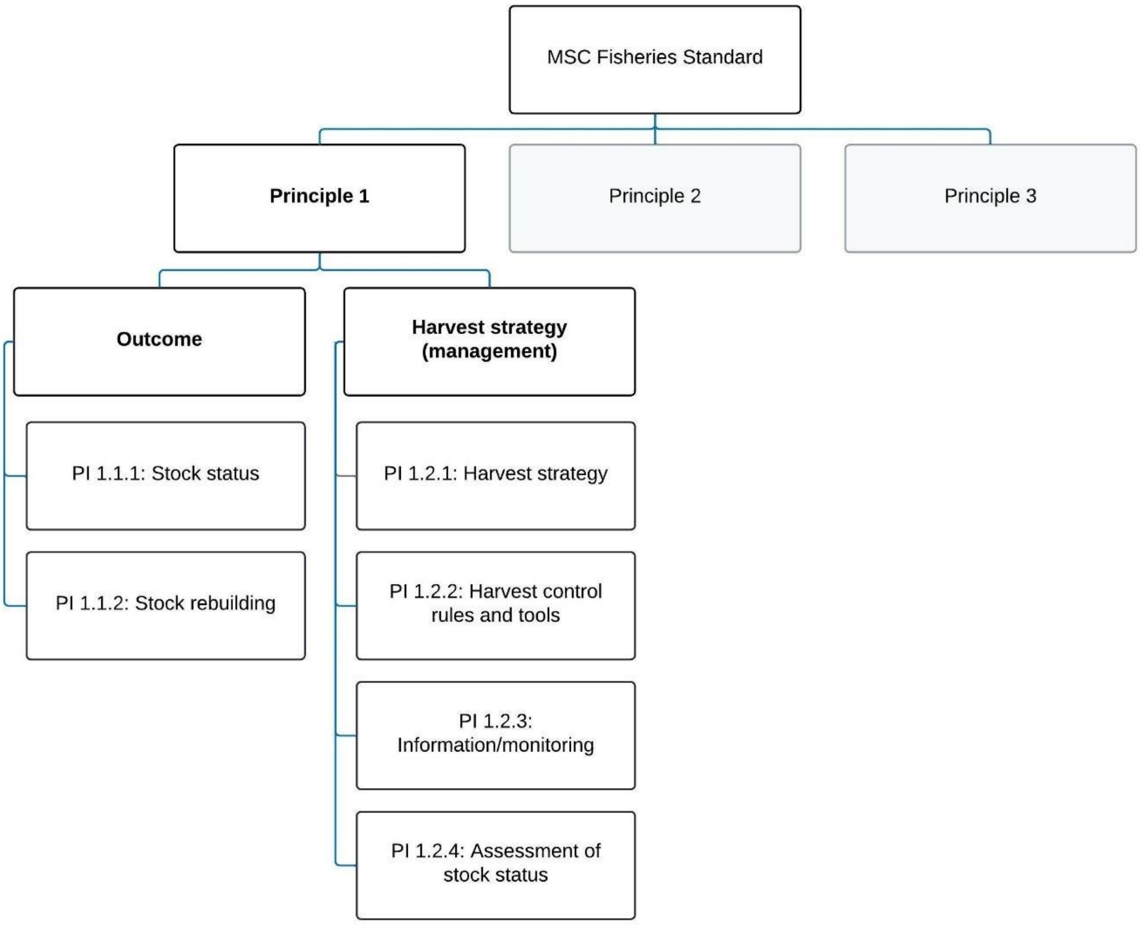

Figure 3: Marine Stewardship Council (MSC) Fisheries Standard v3.0 Principle 1 default assessment tree (Figure SA1 in Marine Stewardship Council 2022).

2.2 Management reference points

The conceptual management objectives, the Fisheries New Zealand Harvest Strategy Standard (Ministry of Fisheries 2011), and the Operational Guidelines for New Zealand's Harvest Strategy Standard (Ministry of Fisheries 2008) were used to define the management reference points (Table 1).

The proxy target for B_{MSY} used for southern blue whiting is 40% B_0. Deterministic B_{MSY} for southern blue whiting on the Campbell Island Plateau was estimated to be ~20% B_0, however, this assumes perfect information of the population and fishery dynamics. In addition, estimation of B_{MSY} usually requires knowledge of the stock recruitment steepness, which is not well determined for southern blue whiting and is assumed to be h=1. Punt et al. (2014) also noted that the impact of the choice of a proxy value will also depend on the form of the HCR, whether allowance is made for uncertainty when setting catch limits, and on constraints imposed on the extent to which catch limits can vary from one year to the next. I note that the 'real world' B_{MSY} will be higher (e.g., see Reed 1978, Bousquet et al. 2008, Bordet & Rivest 2014) and its value is difficult to estimate reliably.

In New Zealand fisheries management, the B_{MSY} proxy is usually assumed at a value that is higher than that for deterministic B_{MSY} (Punt et al. 2014). It has been defined as 30–45% B_0 for New Zealand management of medium productivity species and 35–50% B_0 for low productivity species (Ministry of Fisheries 2011). Based on the productive values from Table 1 of the Operational Guidelines (Ministry of Fisheries 2011), southern blue whiting are likely to be of medium productivity and have a potential range for the target of between 35–50% B_0. A value of 40% B_0 has also been used as the management target in previous assessments (Fisheries New Zealand 2023) and hence, a value of 40% B_0 was used as the target and the proxy for B_{MSY} in the evaluation of Management Procedures (Table 1). Using the operating model as the base case estimation model, a target range for each candidate HCR was evaluated as the inter-quantile range of the estimated spawning stock biomass, i.e., the range of SSB (%B_0) that would be expected to be obtained at least 50% of the time when a specific HCR is used.

Based on the Operational Guidelines (Ministry of Fisheries 2011), two limit reference points were defined, the soft limit (SLRP, 20% B_0) and the hard limit (HLRP, 10% B_0) (Table 1). The HCRs were evaluated for the probability of being above each limit reference point.

Table 1: Definition of the reference points used for the Harvest Control Rules (HCRs).

Code	Reference point
TRP	Target reference point (40% B_0)
TRP_{LB}	Lower bound of the range for the target biomass (defined as the 25% quantile for each HCR)
TRP_{UB}	Lower bound of the range for the target biomass (defined as the 75% quantile for each HCR)
SLRP	Soft limit reference point (20% B_0)
HLRP	Hard limit reference point (10% B_0)

2.3 Harvest Control Rules

Four groups of candidate HCRs (labelled Rules 1–4) were evaluated for each stock, a constant exploitation rate, three exploitation rate ramp rules that started at 0, 10% and 20% B_0 respectively (ramp threshold, rTH) before ramping up to a constant value above 40% B_0, two that ramp from 0 and 20% respectively to a value equal to the target (40%) or the target multiplied by 1-M (i.e., 0.40**x**(1-0.20)=32.0%B_0). The constant and ramp HCRs are shown in Figure 4.

The HCRs used an update frequency of three years, corresponding to the scheduled frequency of surveys and assessments defined in the research plan for southern blue whiting on the Campbell Island Rise (Fisheries New Zealand 2023). Following the management process for SBW 6I, the assessment was assumed to occur every three years and changes in catch are implemented in the subsequent year, hence reproducing the two-year delay in the management response to the estimation of stock status. In addition, various catch limit constraints were added to each set of decision rules; no constraint on changes in catch limits, a 10% threshold for a change before it was applied (minimum Λ%); and a 20% maximum change in catch limit that could be applied (maximum Λ%) representing potential HCRs to limit fluctuations in the catch limit to meet the economic conceptual objectives.

Based on the outcomes of the assessments, SSB was assumed to have a lognormal distributed value with a mean equal to the true SSB and CV=0.18 (Figure 5), and a proxy CV=0.2 was used for the HCR evaluations. The choice of the lognormal was estimated using the methods of Cullen & Frey (1999) implemented in the R package *fitdistrplus* (Delignette-Muller & Dutang 2015) and the stock status from each stock's most recent base case assessments.

Each HCR was evaluated with the above choice of parameters reflecting potential catch constraints giving a total of 16 potential HCRs (Table 2).

Typically, estimates from stock assessments are autocorrelated (Wiedenmann et al. 2015). Estimates of the autocorrelation in the estimated value of SSB from each sequential and updated assessment are difficult to evaluate empirically. However, Wiedenmann et al. (2015) recommended an interannual autocorrelation of 0.7–0.9 based on a simulation study that estimated the amount of temporal autocorrelation in errors of estimated biomass and recruitment from statistical catch at age stock assessment models over a series of scenarios spanning life histories, exploitation levels, recruitment variability, and data quality. That simulation study suggested that medium lived species (M=0.2 y^{-1}) with moderate exploitation had a median autocorrelation of about ρ=0.85 (Table 5 in Wiedenmann et al. 2015). Hence the HCRs were also evaluated assuming (i) no autocorrelation and (ii) a between-assessment autocorrelation, where an annual autocorrelation (lag=1) of ρ=0.947 was used to simulate the biomass estimates for the harvest strategy, giving an approximate 3-year assessment period autocorrelation of ρ=0.85.

Further, the HCRs and selected sensitivity models were evaluated using the base case model SBW 6I stock assessments. Model sensitivities were chosen that reflected the uncertainty in the assessment assumptions including uncertainty in the choice of steepness (*h*) and natural mortality (*M*).

Table 2: Summary of the evaluated Harvest Control Rules (HCRs) for the southern blue whiting SBW 6Iand (i) the biomass index with lognormal CV and bias for each of the ramp thresholds (rTH); and (ii) the minimum change required for a change in catch (Min. Λ (%)) and the maximum level of catch that can be applied in any year (Max. Λ (%)).

Rule	Harvest control rule (HCR)		Biomass index CV	Catch constraints	
	Type	Label		Min. Λ (%)	Max. Λ (%)
Rule-1	Constant	Rule-1.1	0.20	0	–
		Rule-1.2	0.20	10	–
		Rule-1.3	0.20	0	20
		Rule-1.4	0.20	10	20
Rule-2	Ramp (rTh=0.0)	Rule-2.1	0.20	0	–
		Rule-2.2	0.20	10	–
		Rule-2.3	0.20	0	20
		Rule-2.4	0.20	10	20
Rule-3	Ramp (rTh=0.1)	Rule-3.1	0.20	0	–
		Rule-3.2	0.20	10	–
		Rule-3.3	0.20	0	20
		Rule-3.4	0.20	10	20
Rule-4	Ramp (rTh=0.2)	Rule-4.1	0.20	0	–
		Rule-4.2	0.20	10	–
		Rule-4.3	0.20	0	20
		Rule-4.4	0.20	10	20

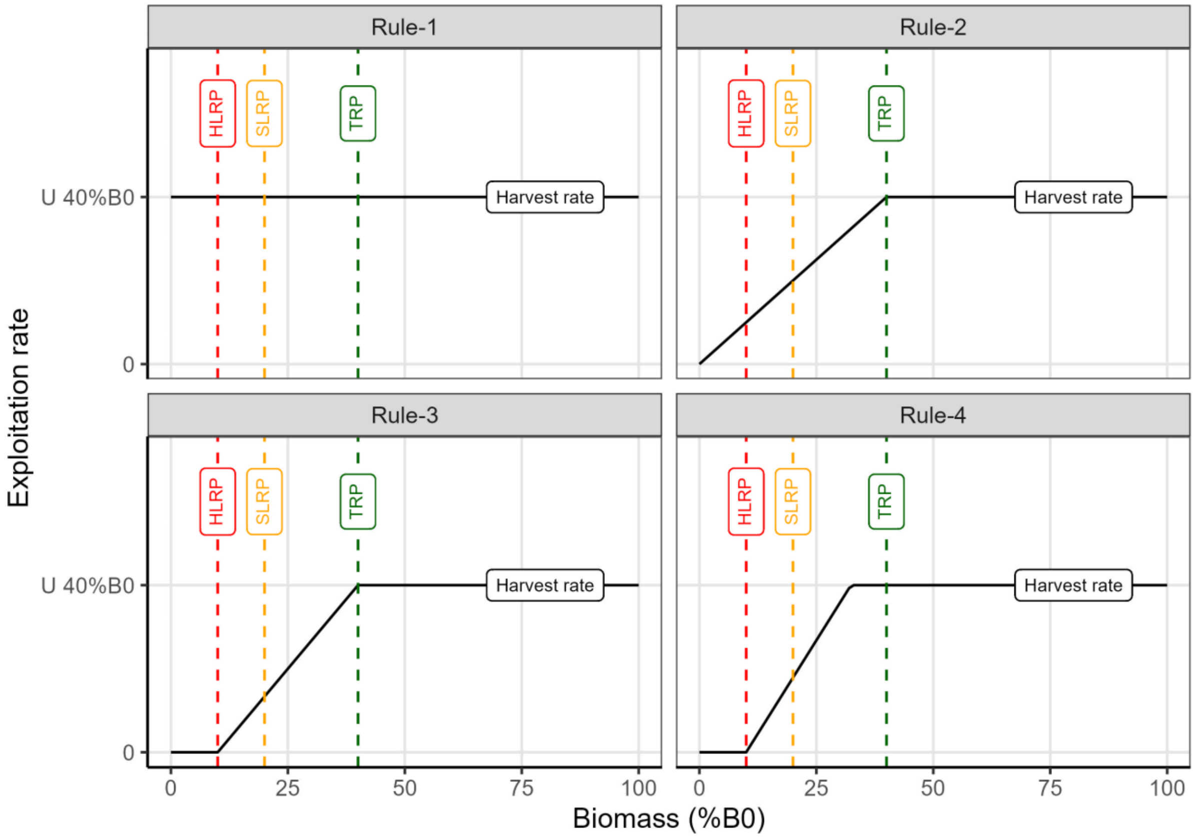

Figure 4: Candidate harvest control rules evaluated for the southern blue whiting SBW 6I stock with (Rule-1) constant harvest rate, (Rule-2) ramp from 0 to 40% B_0, (Rule-3) ramp from 10 to 40% B_0, and (Rule-4) ramp from 10% to (1-M)x40% B_0. Vertical lines indicate the target (green, 40% B_0), soft (orange, 20% B_0), and hard (red, 10% B_0) limits respectively.

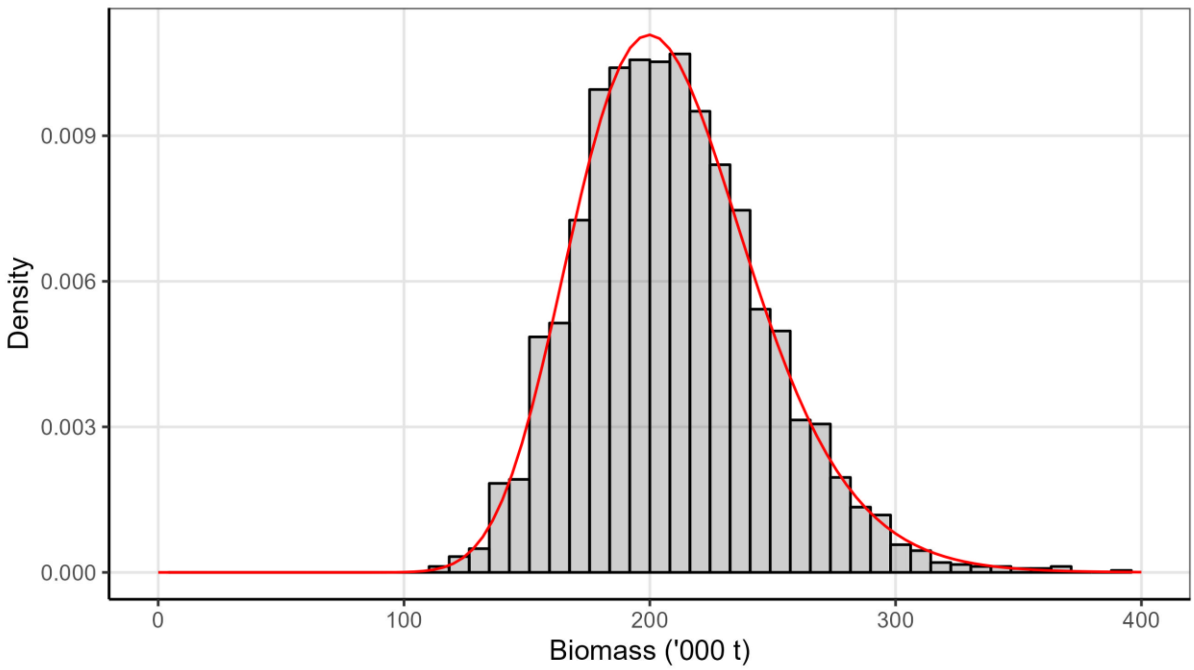

Figure 5: MCMC posterior density of the stock abundance (SSB) in 2022 for the southern blue whiting SBW 6I stock base case assessment (bars) from Doonan et al. (2024), overlaid with a lognormal distribution (red) with parameters μ=206 000 t and CV=0.18).

2.4 Performance Indicators

To evaluate the HCRs against the management objectives and management reference points, a set of performance indicators (PIs) (Table 3) was defined. The performance indicators included criteria relating to the minimum level of spawning biomass required to maintain the productivity of the stock and the limits specified in the Fisheries New Zealand Harvest Strategy Standard (Ministry of Fisheries 2008). The other set of performance indicators related to the utilisation of the stock, and the trade-offs between the overall magnitude of catch and stability in annual catches (Table 3). Selection criteria were also defined for the key performance indicators (Table 4). The results of the simulations (1000 simulations over 100 years) were summarised for each HCR to derive metrics for each performance indicator for the stocks and evaluate if they meet the selection criteria.

Table 3: Performance indicators for evaluating HCRs.

Code	Performance indicator
P01	Median spawning stock biomass relative to the target reference point (TRP)
P02	Median spawning stock biomass relative to B_0
P03	The proportion of years below the hard limit reference point (10% B_0)
P04	The proportion of years below the soft limit reference point (20% B_0)
P05	Proportion of years below 30% B_0
P06	The proportion of years below 35% B_0, the lower bound of target biomass (TRP_{LB})
P07	The proportion of years above 50% B_0, upper bound of target biomass (TRP_{UB})
P08	Proportion of years above 60% B_0
P09	The proportion of years above the target reference point (40% B_0)
C01	Median total annual catch (t)
C02	The standard deviation of total annual catch (t)
C03	The proportion of years with a change in the annual catch of greater than 250 t

Table 4: Selection criteria for the key performance indicators.

Code	Performance indicator	Selection criteria
P03	The proportion of years below the hard limit (10% B0)	<0.01
P04	The proportion of years below the soft limit (20% B0)	<0.05
P05	Proportion of years below 30% B0	<0.10
P06	The proportion of years below the lower bound of the target biomass	<0.25
P07	The proportion of years above the upper bound of the target biomass	<0.25

2.5 Operating models

The base case operating model used the MCMC posterior from the base case assessment model, using an operating model based on the most recent assessment by Doonan et al. (2024). The SBW 6I model was structured as a sex (male and female) and age structured model whereby the number of fish of each age from 2 to 15 was tracked through time, and the last age group was a plus group (i.e., an aggregate of all fish aged 15 and older). Each stock was initialised assuming an unfished equilibrium age structure at an initial biomass (i.e., with constant recruitment) and the initial biomass was estimated by the model. The models were run from the 1960 to 2022 fishing years. The annual cycle was broken into two discrete time steps: a non-spawning time step (November–August) and a spawning time step (September–October) (Table 5) with a single spawning fishery. Biomass calculations at any point in the model were made by multiplying the number of fish in each year class by the size-at-age relationship and the length-weight relationship for each sex separately.

Recruitment was assumed to occur at the beginning of the second (spawning) time step, to be 50:50 male to female, and to be the mean (unfished) recruitment (R_0) multiplied by the spawning stock-recruitment relationship. Recruitment was assumed constant and equal to R_0 times the stock recruitment relationship for years where adequate age composition data were not available (see later). Future (projected) recruitment was assumed to be that obtained from resampling the full time series of estimated year classes (1958–2019) (Doonan et al. 2024).

The catch history is given in Figure 6. Fishing mortality for each fishery was applied by removing half of the natural mortality for the time step, then mortality from the fishery, and then the remaining half of the natural mortality for the time step.

The fishing selectivity parameters were assumed (in the base case) to be logistic and were assumed to be the same for both sexes. Parameters were estimated in the model through the fitting of the fishery's age composition data. Maturation was specified as the time-invariant proportion of male and female fish-at-age that were mature and calculated as at the middle of the summer time step (Doonan et al. 2024).

The primary source of abundance information was the Campbell Island Rise acoustic surveys (Escobar-Flores et al. 2023). Survey selectivities were assumed to be equal to one for mature fish and a constant-by-sex logistic for immature fish. The model then estimated the maturity ogive from the survey and commercial catch age composition data (Doonan et al. 2024).

The length-weight parameters are given in Table 6. Growth for southern blue whiting fluctuates annually and by cohort (Holmes et al. 2023) and an annual sex-specific size-at-age vector is used to determine length (and hence weight) from ages. The stock recruitment relationship was assumed, with steepness h=0.9 (Doonan et al. 2024). Recruitment to the model was at age 2 and all mature fish were assumed to spawn in each year.

Observation data for the southern blue whiting SBW 6I stock assessment included the acoustic biomass indices from the series of Campbell Island Rise surveys from the *Tangaroa* and were available at approximately 3-year intervals from 1992 to 2022. Lognormal errors, with known CVs, were assumed for the survey biomass observations. Age composition observations were available from the immature fish survey and the commercial catch. Multinomial likelihoods were assumed for the age composition data. No ageing error was included in the assessment model (Doonan et al. 2024).

The base case model was described by Doonan et al. (Doonan et al. 2024) and estimated initial spawning stock biomass of 323 000 t (95% credible intervals 292 000–369 000 t) with a current status of 63% B_0 (95% credible intervals 47–82% B_0). Sensitivity models from the assessment described in Doonan (2024) and the models selected for the MP evaluation are summarised in Table 8.

Table 5: Annual cycle of the southern blue whiting stock assessment model from Doonan et al.(2024), giving the time steps, and the timing of biological processes (ageing, recruitment, maturation, growth, natural mortality, and spawning), and observations (resource surveys and associated age compositions (*Tangaroa*), and observer age compositions (ACs)).

Month	Catch (%)	Biology						Observations		Time step
	Assumed	Ageing	Recruitment	Maturation	Growth (%)	Natural mortality	Spawning	Resource surveys	ACs	(Time step label)
Year start		X								
Nov										
Dec										
Jan					0.0		X			
Feb										
Mar						0.90				
Apr										Non-spawning
May										
Jun										
Jul										
Aug										
Sep			X	X						Spawning

Oct	100	0.00	0.10	*Tangaroa* (14 @ 1993–2022)	X
Total	100	1.00	1.00		

Table 6: Assumed biological parameters for the southern blue whiting SBW 6I stock.

Relationship	Reference	Parameter (units)	Value: Both	Male	Female
Natural mortality[1]	(Holmes et al. 2023)	M (y^{-1})		0.21	0.19
Length-weight	(Hanchet 1991)	a ($g.cm^{-1}$)		5.15e-6	4.07e-6
		b		3.092	3.152
Stock recruitment relationship					
Stock recruitment steepness[2]	(Doonan et al. 2024)	h	0.9		
Recruitment variability[3]	(Doonan et al. 2024)	σ_R	1.3		
Proportion male at birth	(Doonan et al. 2024)		0.5		
Proportion of mature that spawn	(Doonan et al. 2024)		1.0		
Maximum exploitation rate[4]	(Doonan et al. 2024)	U_{max}	0.999		

1. Assumed value but also estimated in sensitivity models.
2. Assumed value but also with h = 0.50 and estimated in sensitivity models.
3. Assumed prior but estimated from MCMC values for the projections.
4. Assumed maximum exploitation rate to constrain implausible model estimates.

Table 7: Maturity-at-age for males and females for southern blue whiting on the Campbell Island Rise (Doonan et al. 2024).

Age	1	2	3	4	5	6+
Male	0.000	0.150	0.700	0.950	0.990	0.999
Female	0.000	0.050	0.500	0.110	0.990	0.999

Table 8: Summary of the base case and sensitivity stock assessment models (medians and 95% CIs for the run, description, and MCMC estimates of B_0 and current stock status) from Doonan et al. (2024) and the models that were used as sensitivities in the management procedure (MP) evaluation (highlighted in grey).

Description	Model sensitivity	MP evaluation	B_0	B_{2024} (%B_0)
2023 base	Yes	Yes	336 200 (303 400–375 600)	62 (46–79)
(a) M free (estimated M)	Yes	Yes	327 100 (300 700–361 300)	55 (39–75)
(b) Tvary (time-varying maturation rates)	Yes	No	319 000 (291 000–365 000)	58 (41–79)
(c) Low M	Yes	Yes	326 800 (305 600–351 600)	51 (37–67)
(d) High M	Yes	Yes	408400 (349 300–481 100)	68 (51–87)
(e) Steepness h = 0.5	No	Yes	537 900 (450 400–650 800)	34 (16–57)
(f) Steepness h = 0.66	No	Yes	396 100 (344 200–466 700)	47 (24–76)
(g) Steepness h = 0.100	No	Yes	321 400 (289 400–361200)	64 (48–84)

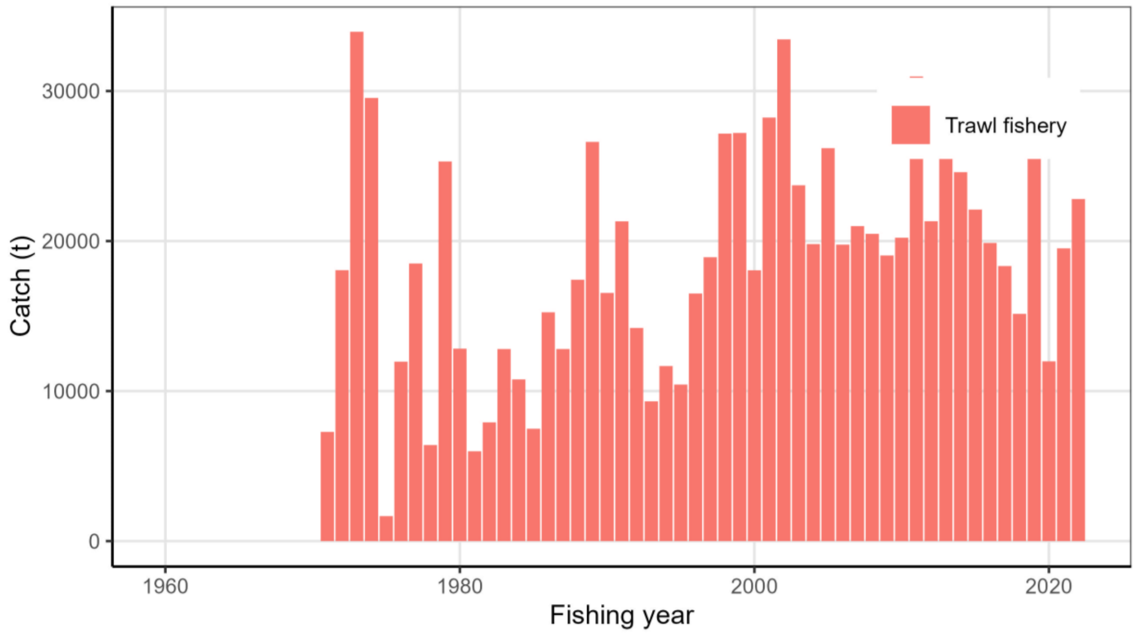

Figure 6: Annual reported catch of southern blue whiting on the Campbell Island Rise for the fishing years 1960 (1959–60) to 2022 (2021–22) from Doonan et al. (2024).

2.6 Management procedure models

The management procedure evaluated the HCRs using the approach outlined in Punt et al. (2016) using proxy estimates of SSB. The first phase of the operating model utilised the model estimates from each stock assessment with the estimated model parameters from the assessment model and commercial catches to determine the population age structure (numbers at age) of the stock in the terminal year of each model. The second phase of the operating model projected the population age structures for 100 years (burn-in phase) and then for a 100-year evaluation period (evaluation phase).

The stock assessment processes are typically computationally intensive, integrating multiple fishery age composition and survey data sets with stock status advice and management based on projections from MCMC estimates. For each evaluation and HCR, the annual estimates of stock status were simulated by sampling from the "true" stock status with an assumed distribution and level of sampling error. The sampling error was assumed lognormally distributed with a CV=0.20 (see Figure 5 above), based on the level of uncertainty associated with the estimate of current stock status from the base case of the most recent stock assessment.

During the evaluation period, the annual fishery catches were set based on the specific candidate HCRs with applied catch from the HCR, with the current catch assumed up until the year of application of the harvest strategy (2026). Following the management process for southern blue whiting, the assessment is assumed to occur in the year following the estimate of stock status (year+1) and changes in catch are implemented in the subsequent year (year+2), i.e., reflecting a delay of two years in the management response to the estimation of stock status.

Recruitment for the future period was resampled from the historical estimated YCS from each model (μ=1.0). This full period (1958–2019) was used, as the most recent 10-year period had a slightly average level of recruitment (μ=1.08). The estimated year classes are shown in Figure 7.

The HCRs were also tested on the base case with the assumption that future recruitment was average or that future recruitment was autocorrelated. For the autocorrelated recruitments, an auto-regressive moving average (ARMA) model was assumed using autoregressive integrated moving average (ARIMA) methods fitted to each MCMC sample with the `auto.arima` in the *R* Forecast package

(Hyndman & Khandakar 2008). We assume the time series of recruitments was stationary (i.e., no integration and hence setting d=0), with mean=0 in log space and they followed an arima(p, 0, q) process, with the sample specific relationship used to simulate unknown recent and future recruitments.

For southern blue whiting in SBW 6I, these were then assumed to be the recruitments for the years after 2019. The resulting ARMA models are given in Figure 8. ARMA model estimates of the first-order autocorrelation are given in Figure 9.

For each candidate HCR, a set of 1000 simulations were conducted based on a random set of the Markov chain Monte Carlo (MCMC) samples from each base case southern blue whiting stock assessment model and an equivalent set of sampled recruitment deviates to determine future recruitments. Further, the HCRs were also evaluated assuming either no inter-assessment autocorrelation (ρ=0) and assuming ρ=0.85, following Wiedenmann et al. (2015).

Hence the HCRs were also evaluated assuming (i) no autocorrelation and (ii) a between-assessment autocorrelation, where an annual autocorrelation (lag=1) of ρ=0.947 was used to simulate the biomass estimates for the harvest strategy, giving an approximate 3-year assessment period autocorrelation of ρ=0.85.

For each HCR, the reference harvest rate ($U_{40\%B0}$) was calculated using the operating model. Catches in each year were then set using the HCRs with the value of $U_{40\%B0}$ and the catch was updated at 3-year intervals. The range of HCRs was configured with base levels of catch associated with each fishery, with approximately 95% allocated to the summer. During the simulation period, annual catches were decreased when the stock was below the lower range of the target biomass or increased when the stock was above the upper range of the target biomass according to the specific HCR (Figure 4 above), and catch constraints (Table 2).

For the base case model, three additional variants of the HCRs were also evaluated. These added constraints to the HCR that either (i) restricted change in catch unless the catch to apply was more than 10% different from the current catch (10% minimum Λ), and (ii) imposed a maximum change of 20% in the catch from the current catch (20% maximum Λ%), or (iii) both restricted changes to 10% and imposed a maximum change of 20% (10% minimum and 20% maximum Λ).

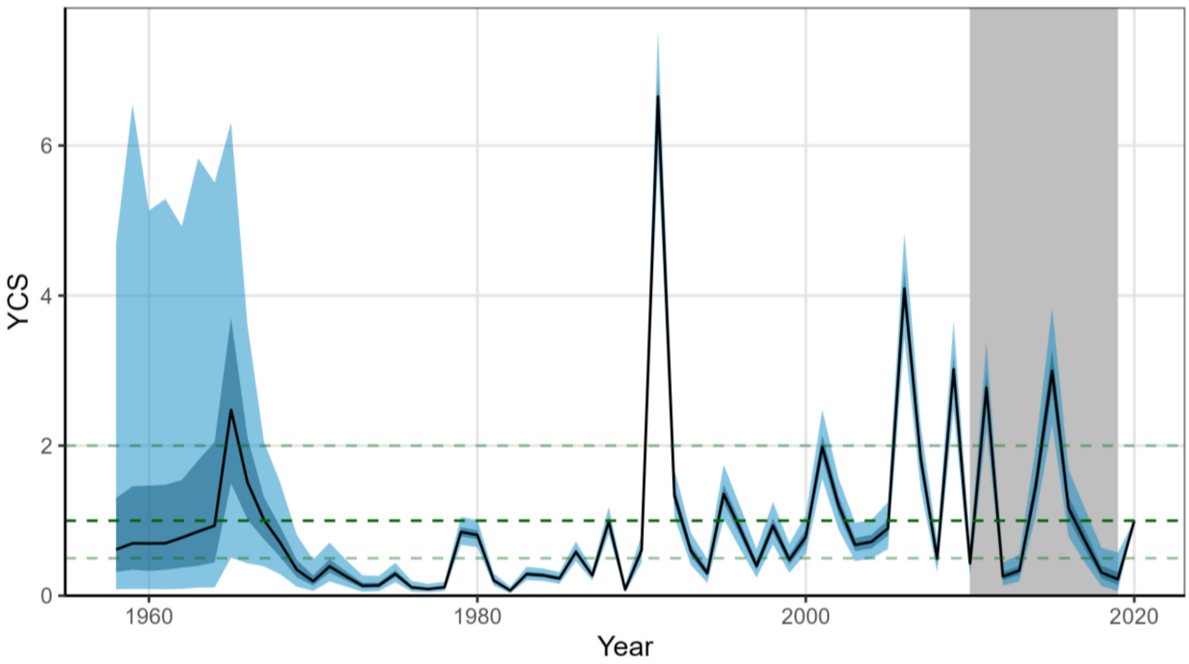

Figure 7: Base case assessment model (Doonan et al. 2024) posterior distribution of year class strengths (YCS) for years 1958–2020 (estimated for 1958–2019). The solid line indicates the median, dark blue shaded area the interquartile range, and the light blue shaded area the 95% CIs. The horizontal dashed green lines indicate the average of 0.5, 1, and 2 respectively. The period of recent estimated YCS (2010–2019) is the period highlighted with the grey background.

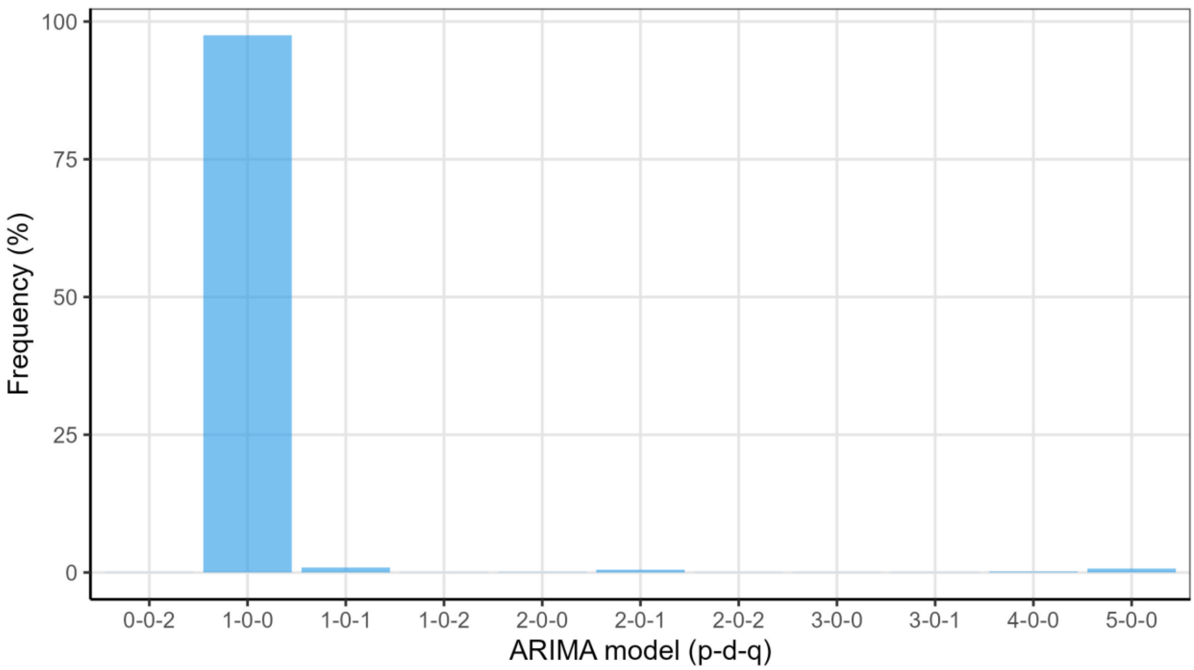

Figure 8: Summary of estimated ARMA models (arima(*p*,*d*,*q*) with d=0) of the historical (1958–2019) YCS from the base case model (Doonan et al. 2024) for southern blue whiting in SBW 6I.

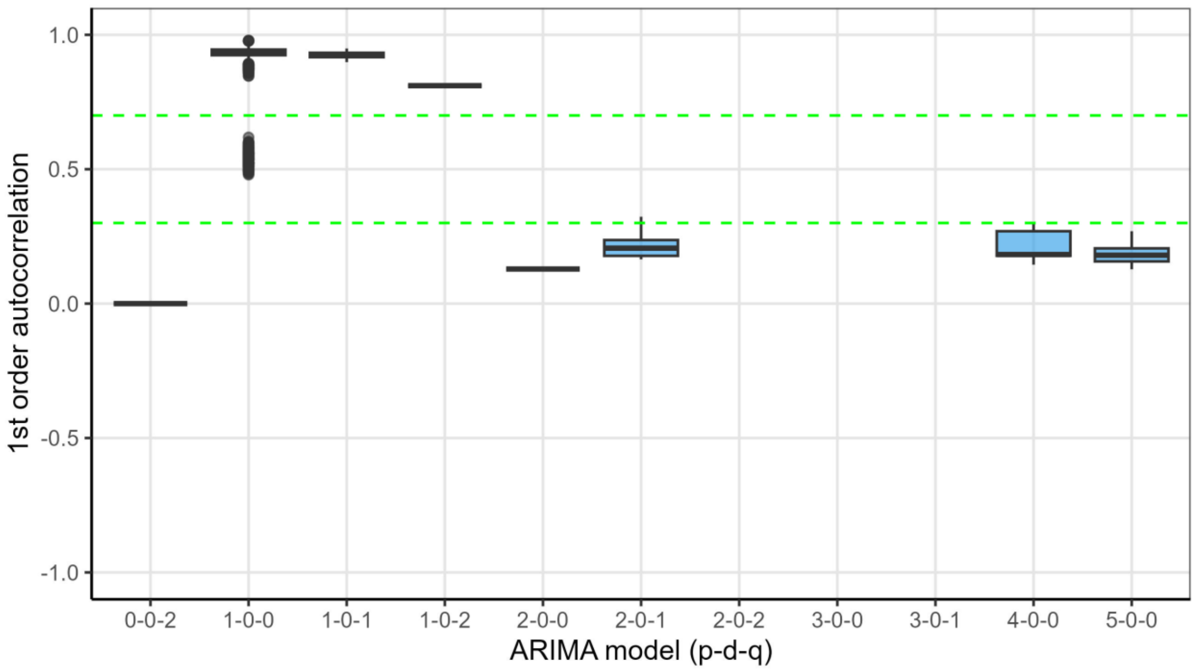

Figure 9: Summary of estimated ARMA models (arima(*p*,*d*,*q*) with d=0) of the historical (1958–2019) YCS from the base case model (Doonan et al. 2024) for southern blue whiting in SBW 6I.

3. RESULTS

3.1 Deterministic B_{MSY}

Deterministic B_{MSY} was estimated assuming a constant harvest rate (U), with perfect knowledge of the stock status and ignoring the hard and soft limit reference point risk probabilities. Estimates were based on the base case assessment models for each stock. The resulting B_{MSY} was 24% B_0 (U=0.385) with a mean annual catch of 30 950 t.

3.2 Base case model estimates of $U_{40\%B0}$

The reference harvest rate ($U_{40\%B0}$) for each HCR is given in Table 9. Long term projections for each HCR assuming YCS at the level of the historical average are given in Figure 10. Values for $U_{40\%B0}$ for each of the HCRs were only slightly different, depending on the rule shape and the catch constraints applied, but were typically about 0.16–0.18. The model uncertainty and the high variability of recruitment led to the soft limit reference point (SLRP) strongly influencing the HCR harvest rate and hence the expected mean biomass from each HCR. Higher values of $U_{40\%B0}$ were obtained with the steeper ramps assumed for each HCR and each scenario.

The estimated catch limits (TACCs) that would be applied using the HCRs are given in Figure 11. Current catch limits were lower, but very similar to that which would be expected from the application of the HCRs, given an estimate of the stock status (median SSB) for the SBW 6I stock of 62% (see Figure 11).

The expected long-term average and standard deviation of the catches are shown in Table 9 with the distribution of expected SSB from the simulations in Figure 12. The probability of the stock status being above 20% and 30% B_0 are shown in Figure 13 and Figure 14 respectively. For all HCRs, the probabilities of being above either 10% or 20% B_0 were all high.

The estimated range of expected values of the SSB (%B_0) under each HCR is given in Table 10. Expected stock status and quantiles, and the probability of being below 10% and 20% B_0 for each HCR are also given in Table 10. All rules had a negligible probability of being below either 10% or 20% B_0. The estimated interquartile range (Table 10) was between 34–47% B_0 for all the HCRS, suggesting that the target range for the southern blue whiting SBW 6I stock could be defined as about 35–50 %B_0, with an associated probability of being inside the target range of about 50%.

Table 9: Estimated values of the Target Reference Point (TRP) and reference harvest rate $U_{TRP\%B0}$ and the expected long term average of the catch (E(catch)) for each candidate HCR using the operating model with the candidate HCR catch constraints (minimum change required for a change in catch (Min. Λ (%)) and the maximum level of catch that can be applied in any year (Max. Λ (%)).

Rule	Harvest control rule (HCR)		Catch constraints		$U_{TRP\%B0}$	E(catch)
	Type	Label	Min. Λ (%)	Max. Λ (%)		
Rule-1	Constant	Rule-1.1	0	–	0.164	26 147
		Rule-1.2	10	–	0.164	26 155
		Rule-1.3	0	20	0.140	22 250
		Rule-1.4	10	20	0.139	22 264
Rule-2	Ramp (rTh=0.0)	Rule-2.1	0	–	0.181	26 359
		Rule-2.2	10	–	0.181	26 340
		Rule-2.3	0	20	0.143	21 748
		Rule-2.4	10	20	0.142	21 760
Rule-3	Ramp (rTh=0.1)	Rule-3.1	0	–	0.186	26 360
		Rule-3.2	10	–	0.185	26 333
		Rule-3.3	0	20	0.144	21 614
		Rule-3.4	10	20	0.144	21 638
Rule-4	Ramp (rTh=0.2)	Rule-4.1	0	–	0.178	26 376
		Rule-4.2	10	–	0.177	26 367
		Rule-4.3	0	20	0.141	21 904
		Rule-4.4	10	20	0.141	21 934

Table 10: Estimated values of the reference harvest rate $U_{40\%B0}$, the expected mean, 25–75% quantiles, and probability of being above 10% and 20% B0 for each candidate HCR using the operating model with the candidate HCR catch constraints (minimum change required for a change in catch (Min. Λ (%)) and the maximum level of catch that can be applied in any year (Max. Λ (%)).

Rule	$U_{40\%B0}$	Mean (%B_0)	SSB %B_0 (25–75% quantiles)	Pr(SSB > 10% B_0)	Pr(SSB > 20% B_0)
Rule-1.1	0.164	42.7	0.29–0.55	0.986	0.899
Rule-1.2	0.164	42.7	0.29–0.55	0.986	0.898
Rule-1.3	0.140	50.7	0.29–0.57	0.958	0.898
Rule-1.4	0.139	50.7	0.29–0.57	0.957	0.895
Rule-2.1	0.181	42.5	0.29–0.61	0.984	0.900
Rule-2.2	0.181	42.5	0.29–0.61	0.984	0.901
Rule-2.3	0.143	52.1	0.32–0.74	0.954	0.897
Rule-2.4	0.142	51.9	0.32–0.74	0.954	0.898
Rule-3.1	0.186	42.6	0.29–0.60	0.983	0.900
Rule-3.2	0.185	42.6	0.29–0.60	0.983	0.901
Rule-3.3	0.144	52.3	0.33–0.76	0.953	0.897
Rule-3.4	0.144	52.2	0.33–0.76	0.952	0.895
Rule-4.1	0.178	42.3	0.29–0.60	0.985	0.900
Rule-4.2	0.177	42.4	0.29–0.60	0.985	0.901
Rule-4.3	0.141	51.5	0.33–0.76	0.956	0.898
Rule-4.4	0.141	51.4	0.33–0.76	0.955	0.896

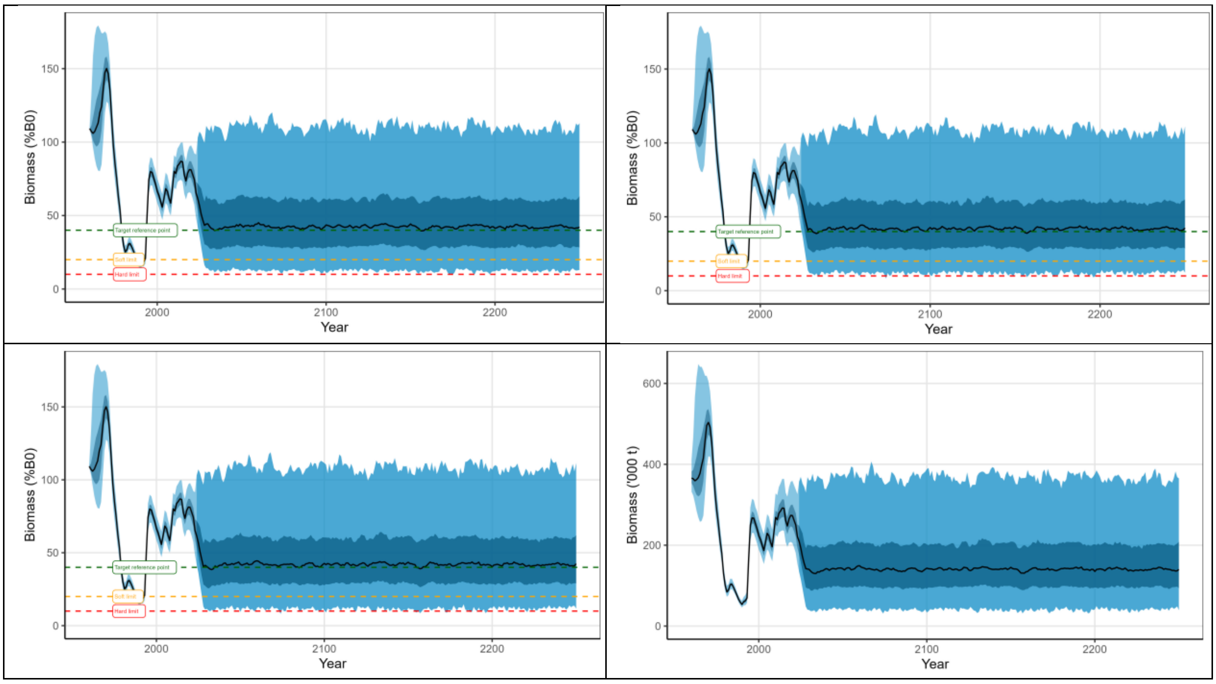

Figure 10: Simulated SSB (%B_0) trends from the base case assessment from Doonan (2024) using four candidate Harvest Control Rules, Rule-1.1 (top left), Rule-2.1 (top right), Rule-3.1 (bottom left), and Rule-4.1 (bottom right). The solid line indicates the median, dark shaded area the interquartile range, and the light shaded area the 95% CIs. Vertical lines indicate the target (green, 40% B_0), soft (orange, 20% B_0), and hard (red, 10% B_0) limits respectively.

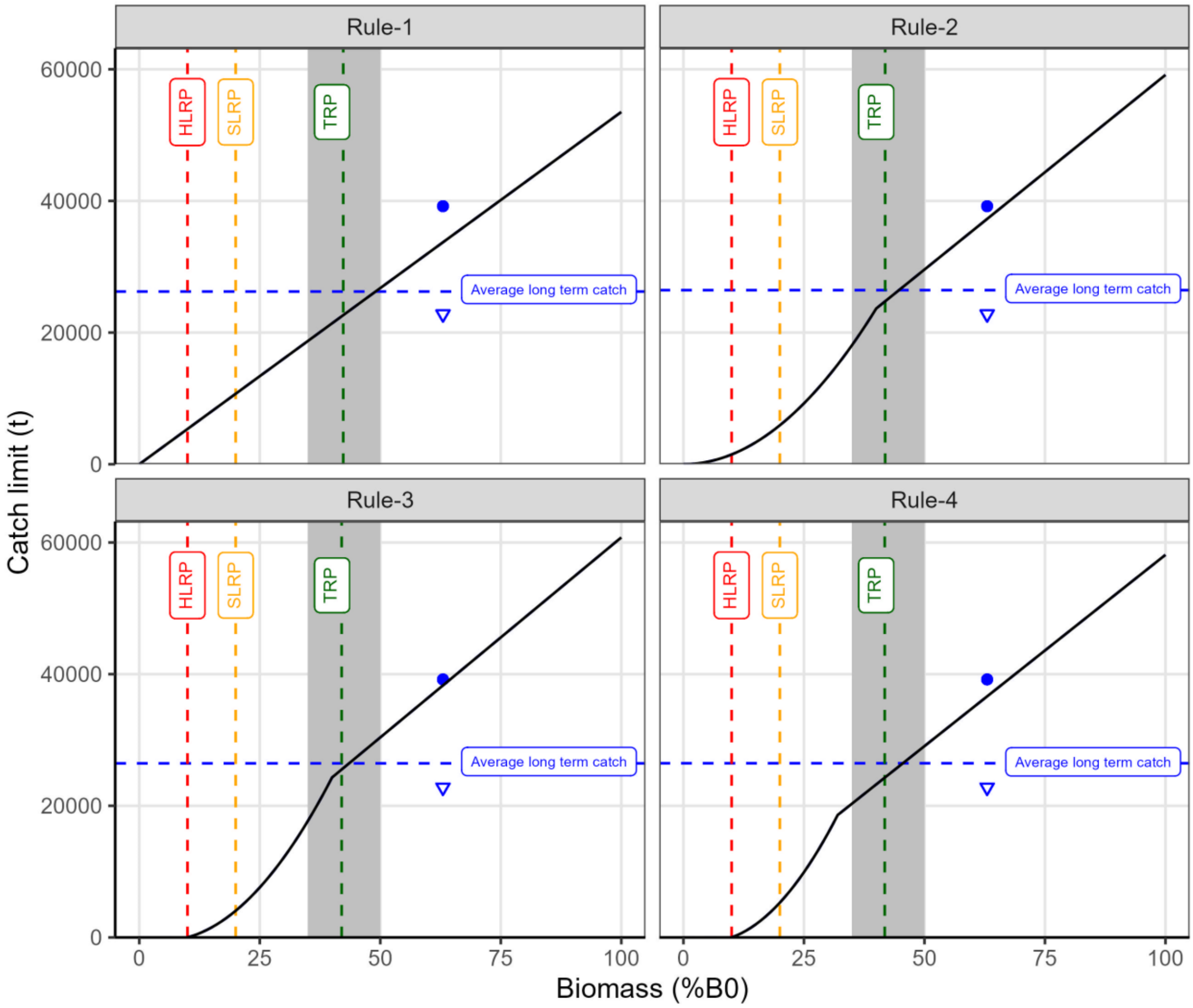

Figure 11: Expected catch limits for southern blue whiting in SBW 6I from the candidate Harvest Control Rules (HCRs). The black line gives the catch limit for the estimated SSB/$B0$ ratio, the horizontal blue dashed line gives the average expected long term catch under the HCR, the blue point indicates the current catch limit for the current (2022) estimated SSB using the 2022 base case model, and the blue triangle indicates the catch taken in the most recent year of the assessment (2022). Vertical lines indicate the target (green, 40% B_0), soft (orange, 20% B_0), and hard (red, 10% B_0) limits respectively. The grey band indicates the target range (35–50 % B_0).

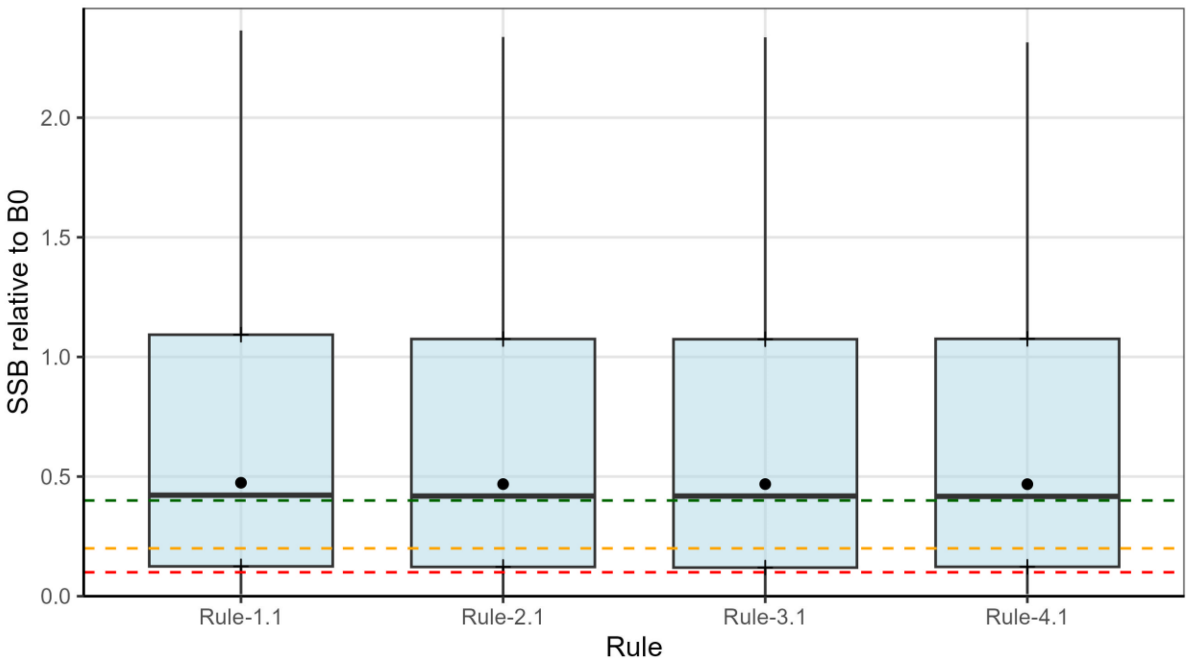

Figure 12: Distribution of the estimated biomass (%SSB) (performance indicator P02) using the reference $U_{40\%B0}$ for each candidate HCR with the base case model with non-constrained catch for Rule-1, Rule-2, Rule-3, and Rule-4. Boxes indicate the 80% quantiles, the horizontal tick gives the 95% quantities, and the range (minimum-maximum) by the vertical line. The bold horizontal line indicates the median and the mean is given by the point. Horizontal dashed lines indicate the target (green, 40% B_0), soft (orange, 20% B_0), and hard (red, 10% B_0) limits respectively.

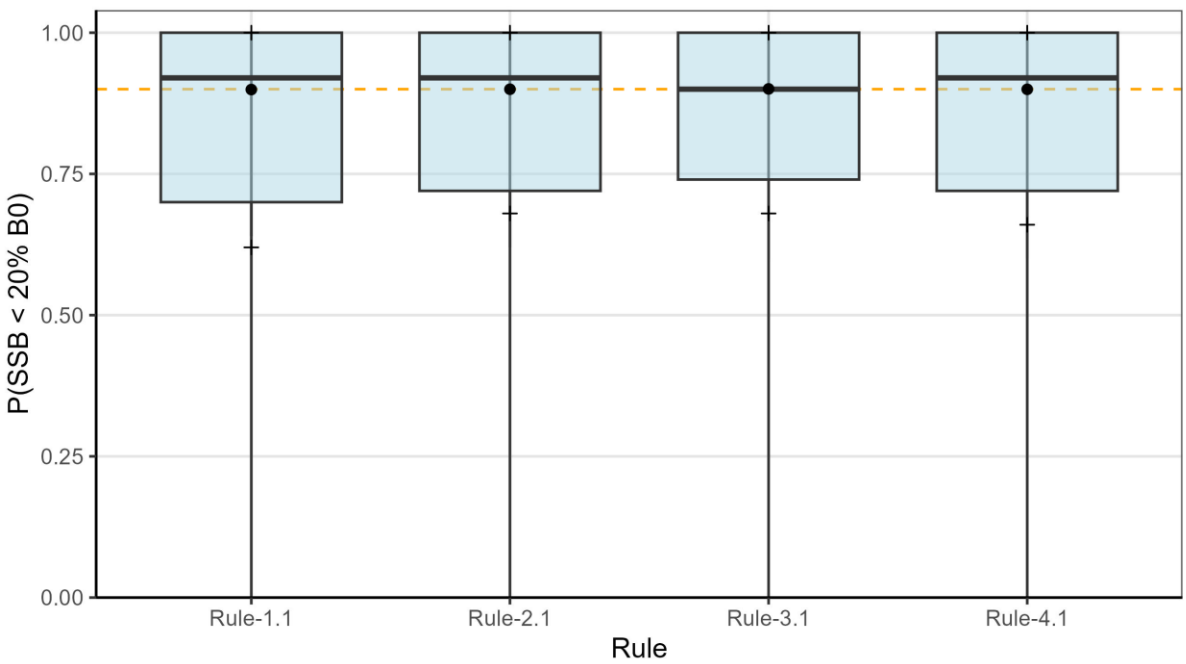

Figure 13: Distribution of the probability of being below the soft limit (SLRP) (performance indicator P04) using the reference $U_{40\%B0}$ for each candidate HCR with the base case model with a non-constrained catch for Rule-1, Rule-2, Rule-3, and Rule-4. Boxes indicate the 80% quantiles, the horizontal tick gives the 95% quantities, and the range (minimum-maximum) by the vertical line. The bold horizontal line indicates the median and the mean is given by the point. The orange horizontal dashed line indicates a 10% probability of being below the soft limit.

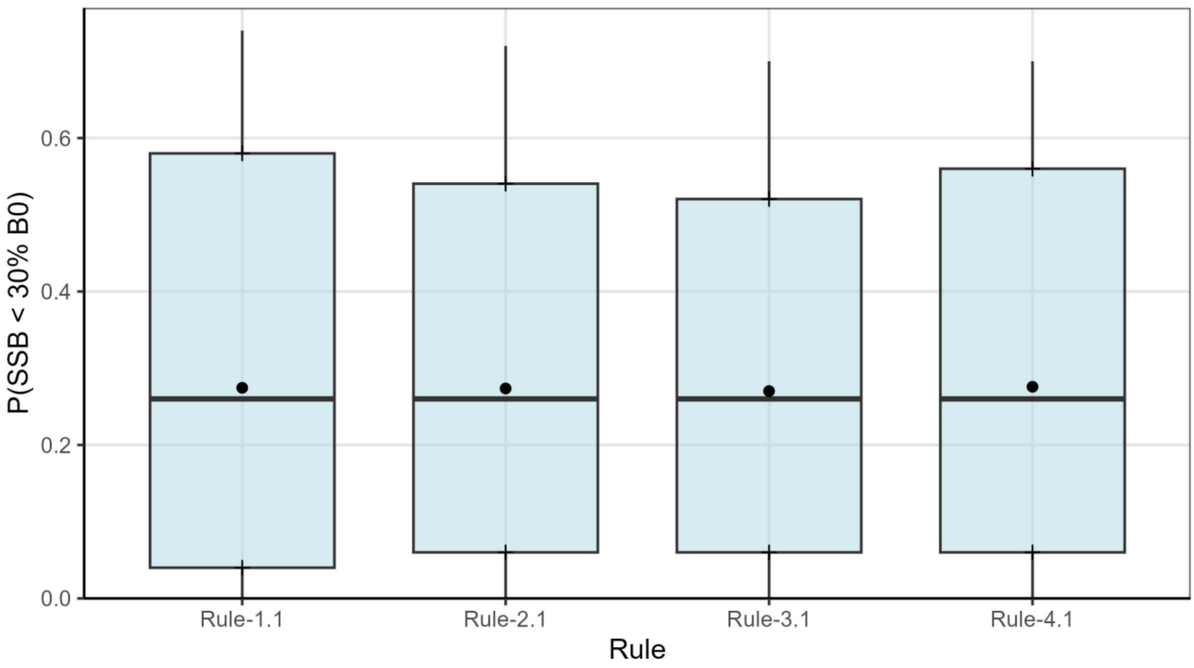

Figure 14: Distribution of the probability of being below 30% B_0 (performance indicator P05) using the reference $U_{40\%B0}$ for each candidate HCR with the base case model with a non-constrained catch for Rule-1, Rule-2, Rule-3, and Rule-4. Boxes indicate the 80% quantiles, the horizontal tick gives the 95% quantities, and the range (minimum-maximum) by the vertical line. The bold horizontal line indicates the median and the mean is given by the point.

3.3 Evaluation of the HCRs with the base case model

The robustness of the HCRs for the southern blue whiting SBW 6I model was evaluated for alternative assumptions of future recruitment, by assuming (i) future year class strengths were similar to the full range of year classes estimated in the base case assessment models (labelled allYCS), (ii) assuming that future year classes followed a stationary ARMA process, estimated for all year classes and standardised to have mean equal to that for the historically estimated period (either 1960–2021) (arimaYCS, see Figure 8 above), (iii) assuming a between-assessment autocorrelation of ρ=0.8 (rho), and (iv) assuming both autocorrelation in year classes using the ARMA process in (ii), as well as between-assessment autocorrelation of ρ=0.8 (arimaYCS_rho).

The expected SSB (%B_0) for each mode and candidate HCR, and each recruitment and assessment autocorrelation scenario after applying the HCR are given in Table 11. Equivalently, the probability of being below the hard and soft limits (HLRP 10%, and SLRP 20% B_0) for each HCR and recruitment and assessment autocorrelation scenario are given in Table 12 and Table 13 respectively. Model sensitivities suggest that assuming recruitment and assessment autocorrelation would maintain the biomass at a level similar to the target of 40% B_0, but the probability of being above 20% B_0 was at or near the lower end of the risk threshold. The expected long-term average catches (C01) for each HCR and scenario are shown in Table 14, with the standard deviations (C02) in Table 15. The proportion of years where a catch limit change takes place (C03) is given in **Error! Reference source not found.**.

Table 11: Expected (mean) values for southern blue whiting in SBW 6I of the performance indicator P02 (SSB %B_0) for each candidate HCR assuming recent YCS (recentYCS), all estimated YCS (allYCS), future YCS following an ARMA process (arimaYCS), assuming autocorrelation in the assessment (rho), and assuming both an ARIMA process for recruitment and autocorrelation in assessments (arimaYCS_rho).

Rule	recentYCS	allYCS	arimaYCS	rho	arimaYCS_rho
Rule-1.1	52.2	47.4	49.2	43.2	34.8
Rule-1.2	52.3	47.4	49.1	43.1	34.9

Rule-1.3	59.9	55.7	60.6	49.3	48.8
Rule-1.4	59.9	55.6	61.4	49.1	48.9
Rule-2.1	50.7	46.9	49.6	40.0	35.3
Rule-2.2	50.8	46.9	49.6	39.9	35.4
Rule-2.3	60.3	56.8	64.3	48.6	53.1
Rule-2.4	60.4	56.9	64.2	48.6	53.1
Rule-3.1	50.4	46.9	49.8	39.2	39.7
Rule-3.2	50.5	46.9	49.9	39.1	39.8
Rule-3.3	60.5	57.1	65.6	48.5	53.8
Rule-3.4	60.3	57.1	65.7	48.2	53.8
Rule-4.1	50.7	46.8	49.9	40.5	40.6
Rule-4.2	50.8	46.8	50.0	40.5	40.7
Rule-4.3	60.1	56.5	64.4	49.0	53.7
Rule-4.4	60.0	56.4	64.7	48.6	53.7

Table 12: Estimated values for southern blue whiting in SBW 6I of the performance indicator P03 (probability of being above 10% B_0) for each candidate HCR assuming recent YCS (recentYCS), all estimated YCS (allYCS), future YCS following an ARMA process (arimaYCS), assuming autocorrelation in the assessment (rho), and assuming both an ARIMA process for recruitment and autocorrelation in assessments (arimaYCS_rho).

HCR	recentYCS	allYCS	arimaYCS	rho	arimaYCS_rho
Rule-1.1	0.99	0.99	0.86	0.81	0.40
Rule-1.2	0.99	0.99	0.86	0.80	0.40
Rule-1.3	0.98	0.96	0.66	0.87	0.49
Rule-1.4	0.98	0.96	0.66	0.86	0.49
Rule-2.1	0.99	0.98	0.92	0.77	0.42
Rule-2.2	0.99	0.98	0.92	0.76	0.42
Rule-2.3	0.98	0.95	0.71	0.86	0.53
Rule-2.4	0.98	0.95	0.70	0.85	0.53
Rule-3.1	0.99	0.98	0.93	0.76	0.49
Rule-3.2	0.99	0.98	0.93	0.75	0.49
Rule-3.3	0.98	0.95	0.71	0.85	0.53
Rule-3.4	0.98	0.95	0.71	0.85	0.53
Rule-4.1	0.99	0.99	0.93	0.78	0.50
Rule-4.2	0.99	0.99	0.93	0.77	0.49
Rule-4.3	0.98	0.96	0.70	0.86	0.53
Rule-4.4	0.98	0.96	0.70	0.85	0.53

Table 13: Estimated values for southern blue whiting in SBW 6I of the performance indicator P04 (probability of being above 20% B_0) for each candidate HCR assuming recent YCS (recentYCS), all estimated YCS (allYCS), future YCS following an ARMA process (arimaYCS), assuming autocorrelation in the assessment (rho), and assuming both an ARIMA process for recruitment and autocorrelation in assessments (arimaYCS_rho).

HCR	recentYCS	allYCS	arimaYCS	rho	arimaYCS_rho
Rule-1.1	0.95	0.90	0.68	0.71	0.35
Rule-1.2	0.95	0.90	0.68	0.70	0.35
Rule-1.3	0.94	0.90	0.59	0.78	0.44
Rule-1.4	0.95	0.90	0.59	0.77	0.44
Rule-2.1	0.94	0.90	0.73	0.66	0.36
Rule-2.2	0.94	0.90	0.73	0.66	0.36
Rule-2.3	0.94	0.90	0.63	0.77	0.48
Rule-2.4	0.94	0.90	0.63	0.77	0.48
Rule-3.1	0.94	0.90	0.75	0.65	0.42
Rule-3.2	0.94	0.90	0.75	0.65	0.42
Rule-3.3	0.94	0.90	0.64	0.77	0.48
Rule-3.4	0.94	0.90	0.64	0.76	0.48
Rule-4.1	0.94	0.90	0.74	0.67	0.43
Rule-4.2	0.94	0.90	0.74	0.67	0.43
Rule-4.3	0.94	0.90	0.63	0.78	0.48

Rule-4.4	0.94	0.90	0.63	0.77	0.48

Table 14: Estimated values for southern blue whiting in SBW 6I of the expected catch (t) (performance indicator C01) for each candidate HCR assuming recent YCS (recentYCS), all estimated YCS (allYCS), future YCS following an ARMA process (arimaYCS), assuming autocorrelation in the assessment (rho), and assuming both an ARIMA process for recruitment and autocorrelation in assessments (arimaYCS_rho).

Rule	recentYCS	allYCS	arimaYCS	rho	arimaYCS_rho
Rule-1.1	28 900	26 147	27 101	22 589	28 900
Rule-1.2	28 876	26 155	27 091	22 408	28 876
Rule-1.3	25 684	22 250	13 195	22 000	25 684
Rule-1.4	25 697	22 264	13 117	21 824	25 697
Rule-2.1	29 407	26 359	27 330	22 682	29 407
Rule-2.2	29 369	26 340	27 315	22 498	29 369
Rule-2.3	25 453	21 748	12 868	21 984	25 453
Rule-2.4	25 418	21 760	12 943	21 801	25 418
Rule-3.1	29 492	26 360	27 277	22 688	29 492
Rule-3.2	29 458	26 333	27 272	22 497	29 458
Rule-3.3	25 392	21 614	12 471	21 985	25 392
Rule-3.4	25 449	21 638	12 575	21 815	25 449
Rule-4.1	29 395	26 376	27 232	22 676	29 395
Rule-4.2	29 368	26 367	27 212	22 485	29 368
Rule-4.3	25 561	21 904	12 700	21 983	25 561
Rule-4.4	25 592	21 934	12 625	21 819	25 592

Table 15: Estimated standard deviation for southern blue whiting in SBW 6I of the expected catch (performance indicator C02) for each candidate HCR assuming recent YCS (recentYCS), all estimated YCS (allYCS), future YCS following an ARMA process (arimaYCS), assuming autocorrelation in the assessment (rho), and assuming both an ARIMA process for recruitment and autocorrelation in assessments (arimaYCS_rho).

Rule	recentYCS	allYCS	arimaYCS	rho	arimaYCS_rho
Rule-1.1	13 895	15 256	32 717	10 288	22 566
Rule-1.2	13 852	15 315	32 776	10 319	22 446
Rule-1.3	8 898	8 939	17 022	8 921	16 563
Rule-1.4	8 830	8 931	16 967	9 006	16 575
Rule-2.1	16 525	18 235	35 719	11 169	23 973
Rule-2.2	16 493	18 254	35 629	11 172	23 826
Rule-2.3	9 320	9 394	16 844	9 204	16 515
Rule-2.4	9 262	9 302	16 869	9 238	16 375
Rule-3.1	17 487	19 294	36 691	11 401	24 515
Rule-3.2	17 460	19 292	36 645	11 406	24 368
Rule-3.3	9 413	9 490	16 705	9 273	16 479
Rule-3.4	9 392	9 472	16 711	9 365	16 330
Rule-4.1	16 043	17 826	35 394	11 009	23 999
Rule-4.2	16 003	17 841	35 260	11 015	23 834
Rule-4.3	9 138	9 275	16 783	9 075	16 374
Rule-4.4	9 110	9 287	16 689	9 184	16 312

3.4 Evaluations of the HCRs using alternative models

For southern blue whiting in SBW 6I, each HCR was run for the base case from Doonan et al. (2024) and selected sensitivity models, and the results for the performance indicators given in Table 16. All sensitivities resulted in the biomass being about the TRP (P02) with a high probability of being above the HLRP (10% B_0) or SLRP (20% B_0), depending on the assumptions within each model. The expected catches under each scenario were between 1100–2500 t.

Table 16: Estimated values for southern blue whiting in SBW 6I of the performance indicators (P01–P09 and C01–C03) for each candidate HCR assuming all YCS. The description of each performance indicator is given in Table 3 above.

Model	Rule	P01	P02	P03	P04	P05	P06	P07	P08	P09	C01	C02	C03
2022 Base case	Rule-1.1	1.19	0.47	0.99	0.90	0.27	0.37	0.38	0.26	0.54	26 147	15 256	0.32
	Rule-2.1	1.17	0.47	0.98	0.90	0.27	0.37	0.37	0.25	0.53	26 359	18 235	0.32
	Rule-3.1	1.17	0.47	0.98	0.90	0.27	0.37	0.37	0.25	0.53	26 360	19 294	0.32
	Rule-4.1	1.17	0.47	0.99	0.90	0.28	0.37	0.37	0.25	0.53	26 376	17 826	0.32
2022 Base case with low M	Rule-1.1	0.96	0.38	0.98	0.85	0.40	0.52	0.22	0.13	0.38	20 455	11 406	0.32
	Rule-2.1	0.98	0.39	0.98	0.88	0.36	0.49	0.23	0.13	0.40	20 385	14 204	0.32
	Rule-3.1	0.99	0.39	0.98	0.88	0.35	0.48	0.24	0.14	0.41	20 324	15 237	0.32
	Rule-4.1	0.97	0.39	0.99	0.87	0.37	0.50	0.23	0.13	0.39	20 431	13 991	0.32
2022 Base case with estimated M	Rule-1.1	1.05	0.42	0.99	0.87	0.34	0.45	0.29	0.18	0.45	22 473	13 088	0.32
	Rule-2.1	1.06	0.42	0.99	0.89	0.33	0.44	0.29	0.18	0.46	22 508	15 920	0.32
	Rule-3.1	1.06	0.43	0.98	0.89	0.32	0.43	0.29	0.18	0.46	22 471	16 950	0.32
	Rule-4.1	1.05	0.42	0.99	0.88	0.33	0.44	0.29	0.18	0.45	22 537	15 623	0.32
2022 Base case with high M	Rule-1.1	1.38	0.55	0.98	0.90	0.25	0.33	0.46	0.35	0.60	36 920	24 631	0.33
	Rule-2.1	1.35	0.54	0.98	0.90	0.25	0.33	0.45	0.34	0.59	37 541	28 534	0.33
	Rule-3.1	1.34	0.54	0.98	0.90	0.25	0.33	0.44	0.33	0.59	37 630	29 853	0.33
	Rule-4.1	1.35	0.54	0.98	0.90	0.25	0.33	0.45	0.34	0.59	37 491	27 939	0.33
2022 Base case with h = 0.5	Rule-1.1	0.59	0.24	0.73	0.42	0.76	0.82	0.09	0.06	0.14	20 608	21 443	0.31
	Rule-2.1	0.79	0.31	0.94	0.66	0.63	0.73	0.13	0.09	0.20	24 302	27 413	0.32
	Rule-3.1	0.83	0.33	0.95	0.72	0.59	0.70	0.14	0.09	0.22	24 681	29 410	0.32
	Rule-4.1	0.79	0.32	0.95	0.67	0.63	0.73	0.13	0.09	0.20	24 406	27 531	0.32
2022 Base case with h = 0.66	Rule-1.1	0.95	0.38	0.96	0.77	0.47	0.57	0.22	0.15	0.34	24 642	17 836	0.32
	Rule-2.1	0.99	0.40	0.97	0.83	0.42	0.53	0.23	0.15	0.37	24 946	21 313	0.32
	Rule-3.1	1.01	0.40	0.97	0.84	0.40	0.52	0.24	0.15	0.38	24 939	22 575	0.32
	Rule-4.1	0.99	0.40	0.98	0.83	0.42	0.54	0.23	0.15	0.37	24 972	21 071	0.32
2022 Base case with h = 1.00	Rule-1.1	1.25	0.50	0.99	0.92	0.24	0.33	0.43	0.30	0.58	26 316	15 059	0.32
	Rule-2.1	1.23	0.49	0.99	0.91	0.24	0.34	0.41	0.29	0.57	26 662	17 966	0.32
	Rule-3.1	1.23	0.49	0.98	0.91	0.24	0.34	0.41	0.28	0.57	26 702	18 993	0.33
	Rule-4.1	1.23	0.49	0.99	0.91	0.24	0.34	0.41	0.29	0.57	26 659	17 536	0.32

4. DISCUSSION

The robustness of the HCRs depends on the assumptions of the underlying base and sensitivity assessment models, particularly the assumption that future recruitment will continue to be at an average level, that acoustic surveys are conducted at three-yearly intervals with associated age composition data, and annual fishery age composition data are available to update the assessment.

The HCRs and MPs were based on the structure of the recent southern blue whiting assessment for SBW 6I (Doonan et al. 2024). While the robustness of the simulations, including a selection of specific HCRs, will be dependent on the assumptions of the stock assessment model, the MPs consider only a subset of uncertainties in the model parameters and assume that the MCMC posterior estimates for the model parameters assessment model incorporate these uncertainties. More generally, the MP evaluation could be extended in future work to simulate model misspecification by the development of independent operating and estimation models.

The MP should be routinely revisited, typically every 3–5 years, as the stock assessment continues to be updated and, specifically, as the level of recent and estimates of future recruitment are updated. The MP should also be reviewed if there is a large-scale or other significant change in the operational or management characteristics of the fishery.

5. MANAGEMENT IMPLICATIONS

Reference points for southern blue whiting in SBW 6I include the management target of 40% B_0, a soft limit reference point of 20% B_0, and a hard limit reference point of 10% B_0. Based on the stock assessment of Doonan et al. (2024), the current stock status is estimated to be above the target, assuming recent year classes were at the level of the historically estimated average in the base case model. Based on the projections in Doonan et al. (2024), the stock status would be about the same over the next five years at the level of the current catch.

The MP evaluation suggested a target biomass range (40–55% B_0) would be appropriate for maintaining the stock above the sustainability threshold of 20% B_0). This would result in the mean biomass being at a level that would fluctuate above the target of 40% B_0. The annual catches evaluated by the HCRs yielded average annual catches of about 25 000 t and a catch limit of between 32 000–40 000 t for 2025 with the current level of recruitment, depending on the choice of HCR. The estimated catch limits (TACCs) that would be applied using the HCRs selected values of SSB (%B_0) are given in Table 17.

Table 17: SBW 6I exploitation rates (*U*) and associated catch limits (t) for values of SSB at 5–95 %B_0 for HCRs Rule-1.1, Rule-2.1, Rule-3.1, and Rule-4.1.

SSB (%B_0)	Rule-1.1 *U*	Rule-1.1 Catch limit	Rule-2.1 *U*	Rule-2.1 Catch limit	Rule-3.1 *U*	Rule-3.1 Catch limit	Rule-4.1 *U*	Rule-4.1 Catch limit
5	0.164	2 676	0.023	370	0.000	0	0.000	0
10	0.164	5 352	0.045	1 479	0.000	0	0.000	0
15	0.164	8 028	0.068	3 327	0.031	1 519	0.040	1 982
20	0.164	10 704	0.091	5 915	0.062	4 052	0.081	5 284
25	0.164	13 380	0.113	9 242	0.093	7 597	0.121	9 908
30	0.164	16 056	0.136	13 308	0.124	12 155	0.162	15 853
35	0.164	18 732	0.158	18 114	0.155	17 725	0.178	20 345
40	0.164	21 408	0.181	23 659	0.186	24 309	0.178	23 252
45	0.164	24 084	0.181	26 617	0.186	27 348	0.178	26 158
50	0.164	26 760	0.181	29 574	0.186	30 387	0.178	29 064
55	0.164	29 436	0.181	32 532	0.186	33 425	0.178	31 971
60	0.164	32 112	0.181	35 489	0.186	36 464	0.178	34 877
65	0.164	34 788	0.181	38 447	0.186	39 502	0.178	37 784
70	0.164	37 463	0.181	41 404	0.186	42 541	0.178	40 690
75	0.164	40 139	0.181	44 361	0.186	45 580	0.178	43 597
80	0.164	42 815	0.181	47 319	0.186	48 618	0.178	46 503
85	0.164	45 491	0.181	50 276	0.186	51 657	0.178	49 410
90	0.164	48 167	0.181	53 234	0.186	54 696	0.178	52 316
95	0.164	50 843	0.181	56 191	0.186	57 734	0.178	55 222

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