Fisheries New Zealand

Tini a Tangaroa

# Management Procedures for hake (*Merluccius australis*) in the Sub-Antarctic and on the Chatham Rise for the 2023–24 fishing year

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## EXECUTIVE SUMMARY

**Dunn, A.[1] (2024). Management procedures for hake (*Merluccius australis*) in the Sub-Antarctic and on the Chatham Rise for the 2023–24 fishing year.**

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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 the west coast South Island hake stock, 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 MP evaluations for two stocks: the Sub-Antarctic and the Chatham Rise stock using the most recent stock assessments for each. The Sub-Antarctic assessment was based using data up to the end of the 2020–21 fishing year and the Chatham Rise using data up to the end of the 2019–20 fishing year.

The indices of abundance for the Sub-Antarctic assessment were the Sub-Antarctic *Tangaroa* resource survey series along with fishery and survey age composition data. The indices of abundance for the Chatham Rise assessment were the Chatham Rise *Tangaroa* resource 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 will be at levels comparable to the most recent 10 years estimated in each stock assessment model.

Estimates from the HCRs suggested a target biomass range of 35–50% $B_0$ for both stocks would maintain the stock well above the sustainability threshold of 20% $B_0$ and at a level that would fluctuate about a target of 40% $B_0$. The annual catches evaluated by the HCRs yielded average annual catches of about 2700 t for the Sub-Antarctic and 950 t for the Chatham Rise, assuming future recruitment at the levels of the most recent ten years. 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 most recent 10 years in the assessment model, that surveys are conducted at two-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 biennial surveys were not conducted.

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

# 1. INTRODUCTION

Hake (*Merluccius australis*) is an important commercially caught species found throughout the middle depths of the New Zealand Exclusive Economic Zone (EEZ) south of 40° S typically in depths of 250–800 m (Hurst et al. 2000). Hake are caught mainly by deepwater demersal trawls usually as bycatch in hoki (*Macruronus novaezelandiae*) target fisheries and with some caught by direct targeting (Dunn et al. 2021a, 2023).

The current management of hake divides the fishery into three Fishstocks (Figure 1): (i) the Challenger Fisheries Management Area (FMA) (HAK 7), (ii) the Chatham Rise FMA (HAK 4), and (iii) the remainder of the EEZ comprising the Auckland, Central, Southeast (Coast), Southland, and Sub-Antarctic FMAs (HAK 1) (see). An administrative Fishstock (with no recorded landings) is also defined for the Kermadec FMA (HAK 10) (Fisheries New Zealand 2023). There are likely to be three main biological stocks of hake. These are the west coast of the South Island (WCSI, HAK 7), the Chatham Rise (HAK 4 and the northern regions in HAK 1 on the western Chatham Rise), and the Sub-Antarctic (southern regions of HAK 1) (Fisheries New Zealand 2023).

Hake stocks have previously been assessed with stock assessments for at least one of the three stocks each year since 1991. Previous assessments of hake were in the 1991–92 fishing year (Colman et al. 1991); 1992–93 (Colman & Vignaux 1992); 1997–98 (Colman 1997); 1998–99 (Dunn 1998); 1999–2000 (Dunn et al. 2000); 2000–01 (Dunn 2001); 2002–03 (Dunn 2003a); 2003–04 (Dunn 2004); 2004–05 (Dunn et al. 2006); 2005–06 (Dunn 2006); 2006–07 (Horn & Dunn 2007); 2007–08 (Horn 2008); 2009–10 (Horn & Francis 2010); 2010–11 (Horn 2011); 2011–12 (Horn 2013a); 2012–13 (Horn 2013b); 2014–15 (Horn 2015); 2016–17 (Horn 2017); 2017–18 (Dunn 2019); 2018–19 (Kienzle et al. 2019); 2019–20 (Holmes 2021); and 2020-21 (Dunn et al. 2021b). The most recent assessment was for the Sub-Antarctic by Dunn et al. (2021b) and for the Chatham Rise by Homes (2021). The next assessment for the Sub-Antarctic is scheduled for 2024–25. There is no scheduled next assessment for the Chatham Rise while catches on the Chatham Rise remain below 360 t per year over two years or 720 t in a single year (Fisheries New Zealand 2022).

In 2021, Dunn et al. (2021b) updated the Sub-Antarctic hake assessment using commercial age composition data, resource survey biomass, and survey age composition observations including available data up to the end of the 2020 fishing year, and using the Bayesian stock assessment software Casal2 (Casal2 Development Team 2024a). The assessment concluded that the spawning stock status in 2021 was about 62% $B_0$ (95% credible intervals 49–75% $B_0$) even though there had been a period of recent weaker than average year classes. Survey biomass indices were available from 1992 to 2021 and are currently undertaken at two-year intervals, with the last in 2023 and the next scheduled for 2025. The survey biomass indices initially decreased after the first few years, but have since fluctuated at about 1500 t.

In 2020, Holmes (2021) updated the Chatham Rise hake assessment using commercial age composition data, resource survey biomass, and survey age composition observations including available data up to the end of the 2020 fishing year, and using the Bayesian stock assessment software CASAL (Bull 2002). The assessment concluded that the spawning stock status in 2020 was about 55% $B_0$ (95% credible intervals 46–66% $B_0$) even though there had been a period of recent weaker than average year classes. Survey biomass indices were available from 1992 to 2020 and are currently undertaken at two-year intervals. The survey biomass indices decreased until the 2000 fishing year, and have since fluctuated at about 1500 t. Since the update by Holmes (2021), no further assessments for hake on the Chatham Rise have been undertaken.

The development of Management Procedures (MP, also known as Management Strategy Evaluations) (Butterworth & Punt 1999, Butterworth 2007) for hake 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.

Previously, Horn et al. (2018) explored the effect of catch underestimate claims for hake and found that while alternative catch histories were higher than the base catches in most years, the estimates of the initial and current biomass were higher than the base case models for the west coast South Island, Chatham Rise, or Sub-Antarctic stocks from Horn (2015, 2017) and the estimates of current stock status ($\%B_0$) were similar.

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 not previously been conducted for any New Zealand hake stocks except for the recent work for hake in HAK 7 (Dunn 2024a). This report provides an evaluation of a set of candidate MPs for Sub-Antarctic hake (Dunn et al. 2021b) and the Chatham Rise (Holmes 2021), based on the methods developed by Dunn (2024a). This report was funded by the Seafood New Zealand Deepwater Council, with the specific objectives “to develop a Management Strategy Evaluation for hake 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”.

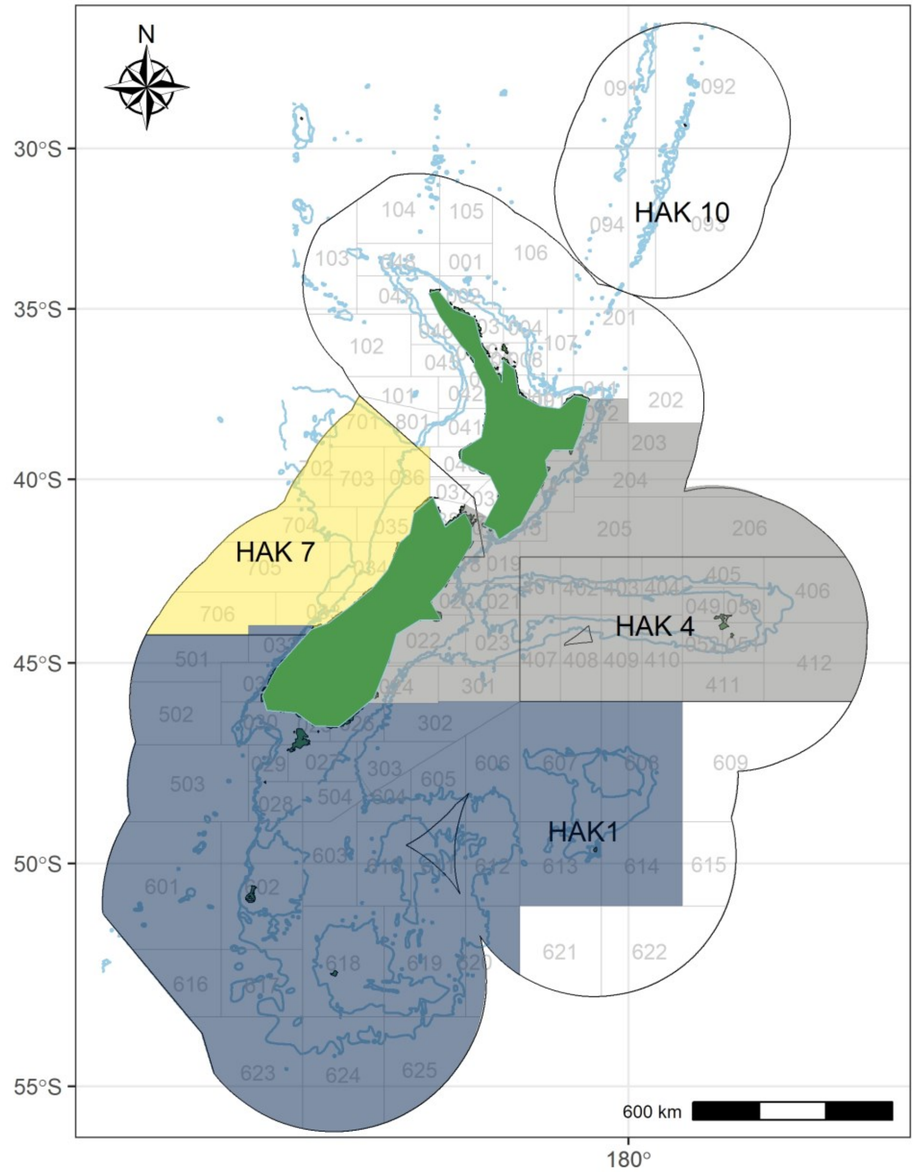


**Figure 1: Quota Management Areas (QMAs) HAK 1, 4, 7, and 10 (black lines), statistical areas (grey), and hake biological stock boundaries: west coast South Island (yellow), Chatham Rise (light grey), and Sub-Antarctic (dark grey).**

## 2. METHODS

### 2.1 Management objectives

The MPs were based on an operating model using the most recent stock assessments for each area and the MPs were undertaken using the same methods as Dunn (2024a). The assessment models assumed each area was a single stock, with the models implemented in implemented in CASAL (Bull 2002). For the MPs, the assessment models were  first converted to 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 (2024a). 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 hake as a Tier 1 species, which are high volume and/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 hake 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 Sub-Antarctic (HAK 1) stock 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. Maintain a constant mean weight of fish in the catch.
   iii. 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).

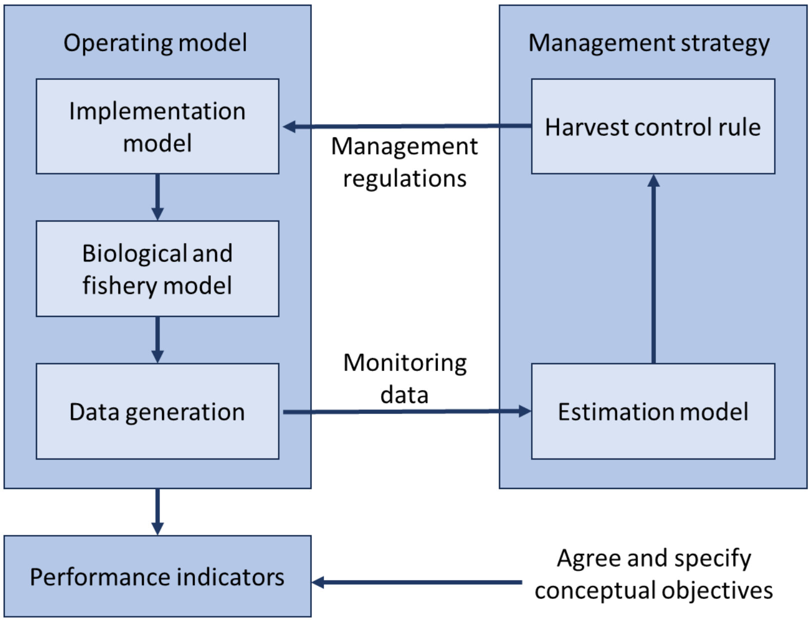


**Figure 2: Conceptual overview of the management strategy evaluation modelling process (Figure 1 in Punt et al. 2016).**

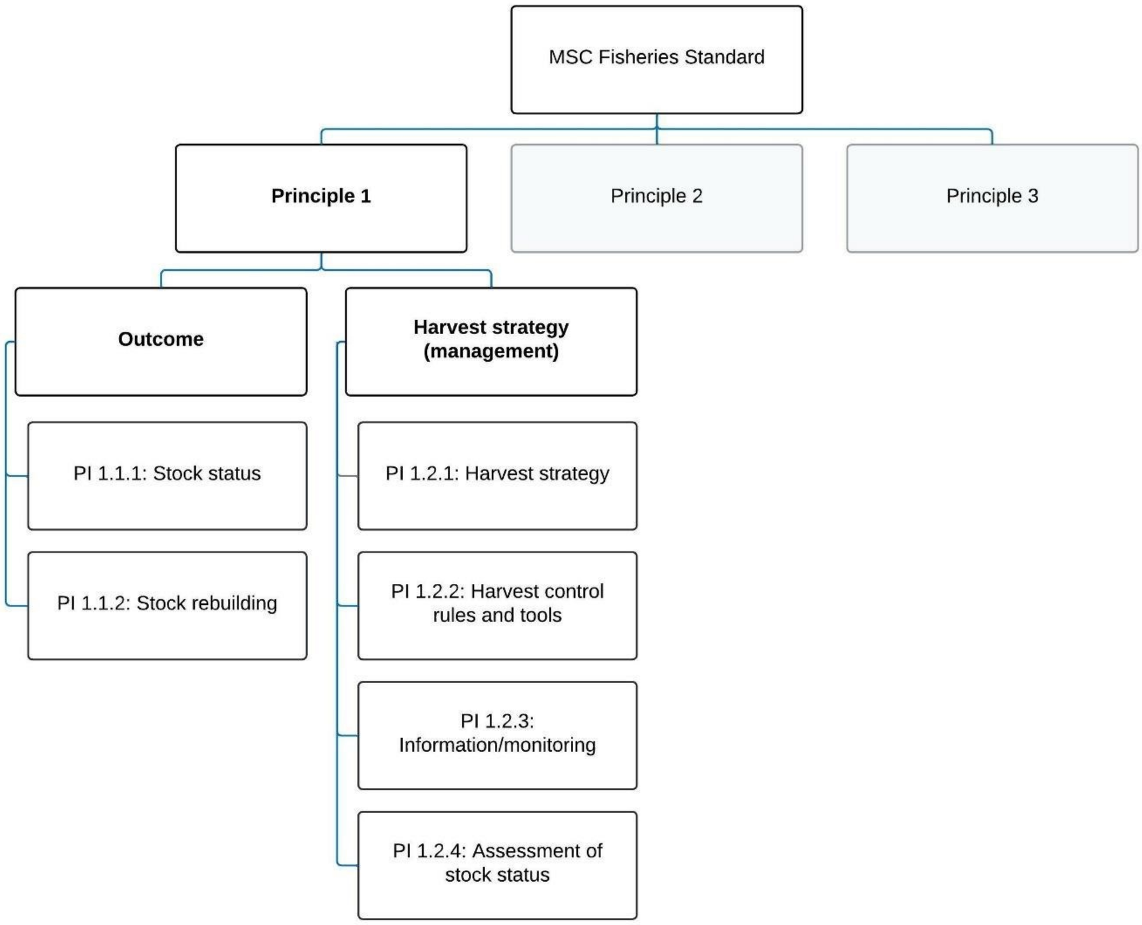


**Figure 3: Marine Stewardship Council (MSC) Fisheries Standard v3.0 Principle 1 default assessment tree (Figure SA1 in Marine Stewardship Council 2022).**

## 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 was 40% $B_0$. Deterministic $B_{MSY}$ for hake in both the Sub-Antarctic and the Chatham Rise was estimated to be ~20% $B_0$, however, this assumed perfect information of the population and fishery dynamics. In addition, estimation of $B_{MSY}$ usually requires knowledge of the stock recruitment steepness, which was found to be poorly determined for hake (see Dunn 2024b). 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) and 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), hake are likely to be either at the low end of medium productivity species or high end of low productivity species 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., $0.40\times(1-0.19)=32.4\%B_0$). 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 both the Chatham Rise and Sub-Antarctic stocks (Fisheries New Zealand 2023). Following the management process for hake, 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=0.30 for the Sub-Antarctic (Figure 5) and CV=0.21 for the Chatham Rise (Figure 6). 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 $\rho$=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 $\rho$=0.947 was used to simulate the biomass estimates for the harvest strategy, giving an approximate 3-year assessment period autocorrelation of $\rho$=0.85.

Further, the HCRs were evaluated using the base case models for the Sub-Antarctic and Chatham Rise stock assessments and selected sensitivity models. 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 Sub-Antarctic (SA) and Chatham Rise (CR) and (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 | SA | CR | Min. Λ (%) | Max. Λ (%) |
| Rule-1 | Constant | Rule-1.1 | 0.30 | 0.21 | 0 | – |
| | | Rule-1.2 | 0.30 | 0.21 | 10 | – |
| | | Rule-1.3 | 0.30 | 0.21 | 0 | 20 |
| | | Rule-1.4 | 0.30 | 0.21 | 10 | 20 |
| Rule-2 | Ramp (rTh=0.0) | Rule-2.1 | 0.30 | 0.21 | 0 | – |
| | | Rule-2.2 | 0.30 | 0.21 | 10 | – |
| | | Rule-2.3 | 0.30 | 0.21 | 0 | 20 |
| | | Rule-2.4 | 0.30 | 0.21 | 10 | 20 |
| Rule-3 | Ramp (rTh=0.1) | Rule-3.1 | 0.30 | 0.21 | 0 | – |
| | | Rule-3.2 | 0.30 | 0.21 | 10 | – |
| | | Rule-3.3 | 0.30 | 0.21 | 0 | 20 |
| | | Rule-3.4 | 0.30 | 0.21 | 10 | 20 |
| Rule-4 | Ramp (rTh=0.2) | Rule-4.1 | 0.30 | 0.21 | 0 | – |
| | | Rule-4.2 | 0.30 | 0.21 | 10 | – |
| | | Rule-4.3 | 0.30 | 0.21 | 0 | 20 |
| | | Rule-4.4 | 0.30 | 0.21 | 10 | 20 |

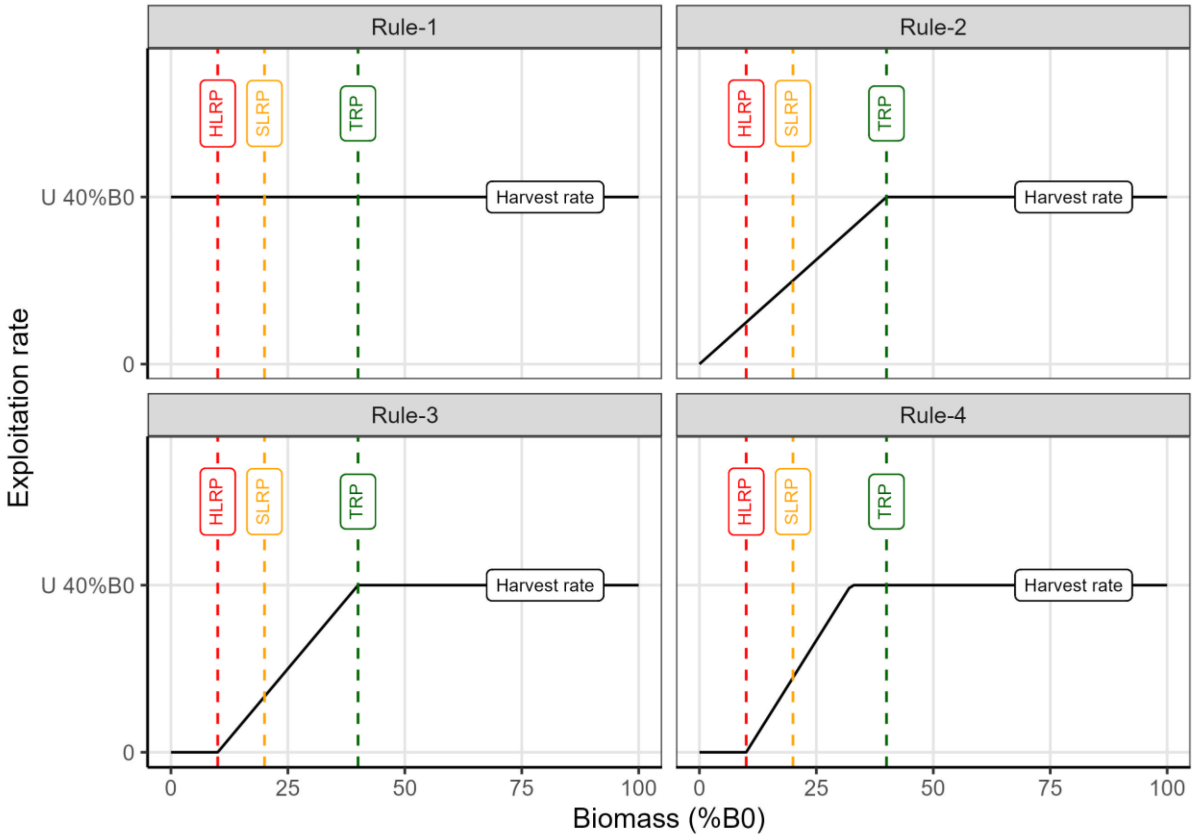


**Figure 4: Candidate harvest control rules evaluated for the Sub-Antarctic hake and Chatham Rise stocks with (Rule-1) constant harvest rate, (Rule-2) ramp from 0 to 40% $B_0$, (Rule-3) ramp from 10 to 40% $B_0$, and (Rule-4) ramp from 10% to (1-*M*)x40% $B_0$. Vertical lines indicate the target (green, 40% $B_0$), soft (orange, 20% $B_0$), and hard (red, 10% $B_0$) limits respectively.**

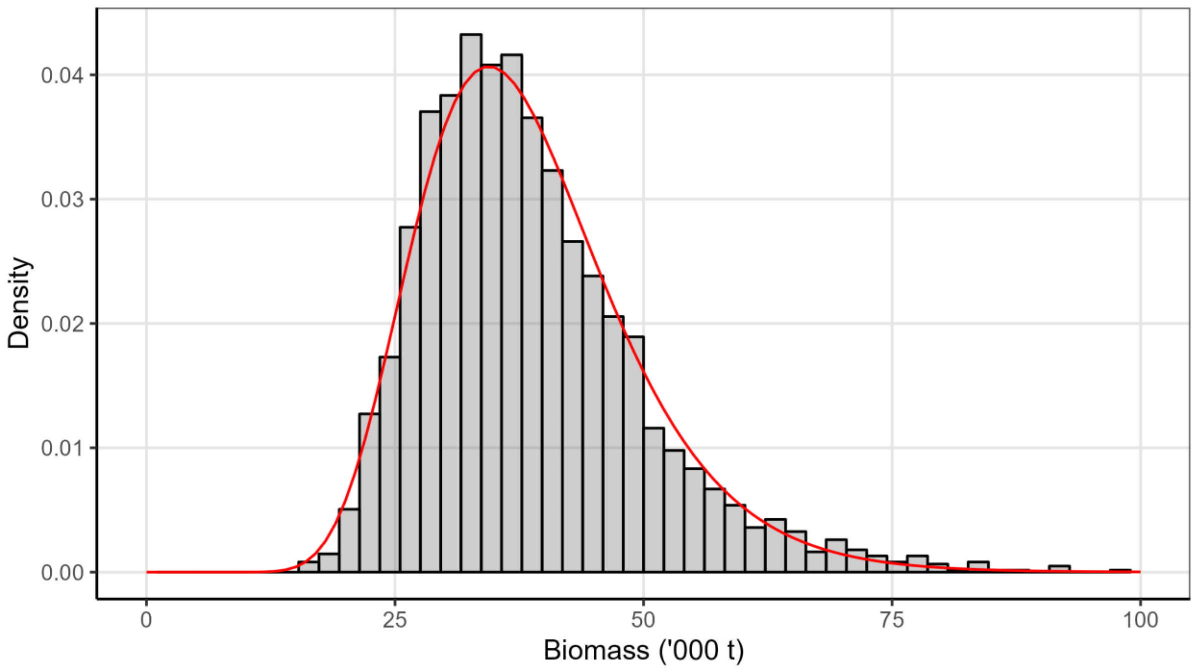


**Figure 5: MCMC posterior density of the stock abundance (SSB) in 2021 for the Sub-Antarctic hake base case assessment (bars) from Dunn et al. (2021b), overlaid with a lognormal distribution (red) with parameters $\mu$=37 100 t and CV=0.29).**

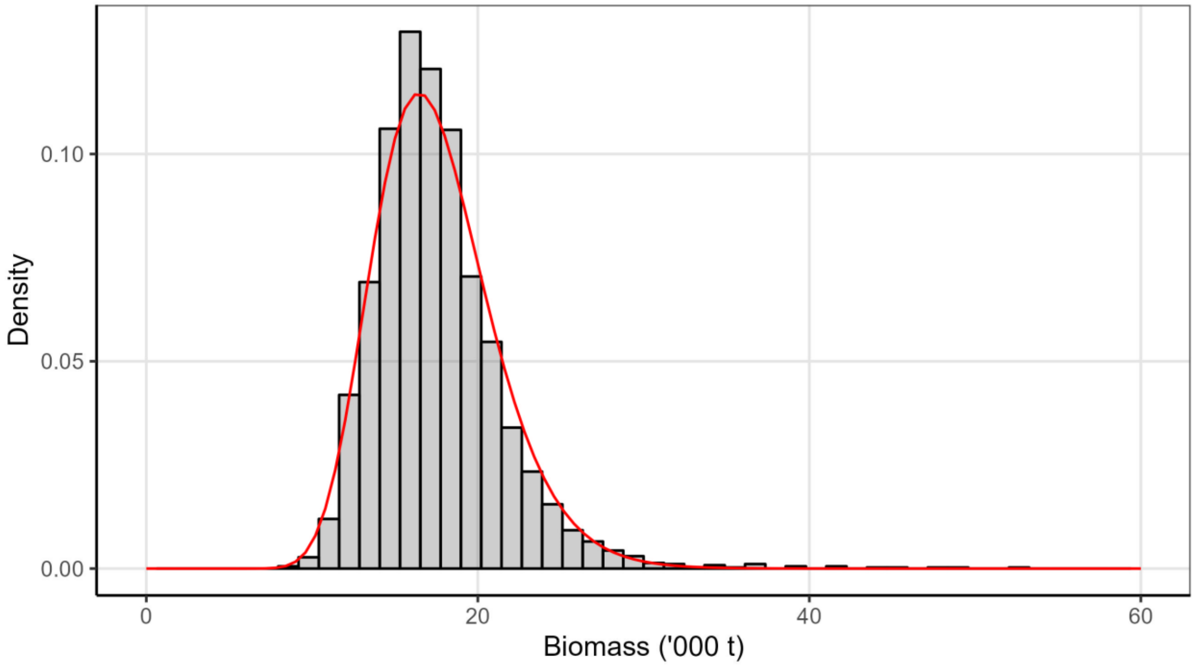


**Figure 6: MCMC posterior density of the stock abundance (SSB) in 2020 for the Chatham Rise base case assessment (bars) from Holmes (2021), overlaid with a lognormal distribution (red) with parameters $\mu$=17 200 t and CV=0.21).**

## 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 models used the MCMC posterior for each of the base case assessment models. The Suib-Antarctic model was structured as a sex (male and female) and age structured model while the Chatham Rise model was unsexed. Both modelled ages from 1 to 30, whereby the number of fish of each age from 1 to 30 was tracked through time, and the last age group was a plus group (i.e., an aggregate of all fish aged 30 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 1975 to 2021 or 2020 fishing years for the Sub-Antarctic and Chatham Rise respectively. The Sub-Antarctic annual cycle was broken into three discrete time steps: an age incrementation step (September), summer (October–March), and winter (April–August) (Table 5). Similarly, the Chatham Rise has three discrete time steps: summer (September–February), autumn (March–May), and winter (June–August), with fishing assumed to occur during the summer time step only (Table 6) and split into two fisheries: western (west of 180° latitude) and eastern (east of 180° latitude). 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.

In the Sub-Antarctic, recruitment was assumed to occur at the beginning of the second (summer) 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 most recent ten years of estimated recruitments (2007–2016) (Dunn et al. 2021b). For the Chatham Rise, recruitment occurred at the start of the first time step and future recruitment was assumed to be obtained from resampling the most recent ten years of estimated recruitments (2008–2017) (Holmes 2021).

In the Sub-Antarctic, a substantial proportion of hake catch was taken in September month of the early years (1990–1994) when catch and effort data were available for the fishery. This proportion was more likely to be similar in characteristics to the catch taken in October–December (the period of the year when more than three quarters of the catch was taken), and hence catch and effort from September was assigned to the following fishing year.

The catch history for each area and fishery is given in Figure 7 (Sub-Antarctic) and Figure 8 (Chatham Rise). 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 (Dunn et al. 2021b).

The primary source of abundance information was the Sub-Antarctic trawl surveys, with the November series forming a consistent time series since 1992. Survey selectivities were assumed double normal and were assumed to be the same for each sex. The model estimated them by fitting the survey age composition data (Dunn et al. 2021b).

The length-weight and growth curve parameters for the Sub-Antarctic are given in Table 7 and the Chatham Rise in Table 8. Parameters for natural mortality were estimated by Horn & Francis (2010), based on age data using methods of Ricker (1975), Hoenig (1983), and Chapman & Robson (1960). The stock recruitment relationship was assumed, with steepness $h$=0.8 from Horn & Francis (2010). Ageing error from the values given by Horn & Francis (2010). Maturity values were from (Horn 2008) (Table 9). Recruitment to the models was at age 1 and all mature fish were assumed to spawn in each year.

The reported catch history of hake in each of the Quota Management Areas (QMA) is given in Dunn et al. (2021b). In the Sub-Antarctic, reported landings peaked at almost 4000 t in 1993–94 and have since slowly declined to about 1000 t in the most recent years; the Total Allowable Commercial Catch (TACC) for hake has been 3701 t since 2001–02, reduced from the TACC of 3632 t that had been set in 1994–95. On the Chatham Rise, reported landings, after adjusting for misreporting (Dunn 2003b) were generally high during the late 1990s, but since about 2010 have been less than 1000 t and have dropped to less than 500 t in recent years.

Observational data for the Sub-Antarctic hake stock assessment included the biomass indices from the core strata from the series of Sub-Antarctic resource surveys from the *Tangaroa*. Survey biomass indices from the November-December survey are available from 1992 to 2021, with the April–May survey available for 1992–1998. Lognormal errors, with known CVs, were assumed for the resource survey biomass observations. Age composition observations for the trawl survey series were available for each of the surveys and were included as unsexed age composition data. Commercial age composition data (Saunders et al. 2021, Ballara et al. 2022) were available for most years and included as unsexed age composition proportions. The commercial fishery age composition data were assumed to be observations of the removals from the summer fishery. No observations were available for the winter fishery, and its selectivity was assumed to be the same as for summer.

Observational data for the Chatham Rise hake stock assessment included the biomass indices from the core strata from the series of Chatham Rise resource surveys from the *Tangaroa*. Survey biomass indices from the January-February survey are available from 1992 to 2020. Lognormal errors, with known CVs, were assumed for the resource survey biomass observations. Age composition observations for the trawl survey series were available for each of the surveys and were included as unsexed age composition data. Commercial age composition data (Saunders et al. 2021, Ballara et al. 2022) were available for most years and included as unsexed age composition proportions. The commercial fishery age composition data were assumed to be observations of the removals from both the western and eastern fisheries during the summer time-step.

Multinomial likelihoods were assumed for the age composition data. Ageing error was accounted for by modifying the likelihoods for the age composition data such that $E_i$ was replaced by $E'_i$, where $E'_i$ were the expected age composition proportions multiplied by an ageing error misclassification matrix $A$. The error misclassification matrix was derived from a normal distribution with constant CV=0.08 (Horn & Francis 2010).

The base case model for the Sub-Antarctic was described in Dunn et al. (2021a) and suggested an initial spawning stock biomass of 59 000 t (95% credible intervals 43 220–93 600) with current status of 62% $B_0$ (95% credible intervals 49–75% $B_0$). Sensitivity models from the assessment described in (Dunn et al. 2021b) and the models selected for the MP evaluation are summarised in Table 10.

The base case model for the Chatham Rise was described in Holmes (2021) and suggested an initial spawning stock biomass of 32 838 t (95% credible intervals 28 280–42 721) with current status of 55% $B_0$ (95% credible intervals 46–66% $B_0$). Sensitivity models from the assessment described in Holmes (2021) and the models selected for the MP evaluation are summarised in Table 11.

**Table 5: Annual cycle of the Sub-Antarctic hake stock assessment model from Dunn et al. (2021b), 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 | | | | | | | | Ageing |
| Sep | | | X | | | | | | | Summer |
| Oct | | | | | | | | | | |
| Nov | | | | | | | | | | |
| Dec | | | | | | | | | | |
| Jan | 78 | | | X | 0.0 | 0.58 | X | | X | |
| Feb | | | | | | | | | | |
| Mar | | | | | | | | | | |
| Apr | | | | | | | | *Tangaroa* (4 @ 1992–1998) | X | |
| May | | | | | | | | | | |
| Jun | | | | | | | | | | Winter |
| Jul | 21 | | | | 0.33 | 0.42 | | *Tangaroa* (19 @ 1992–2021) | X | |
| Aug | | | | | | | | | | |
| Year end | | | | | | | | | | |
| Total | 100 | | | | 1.00 | 1.00 | | | | |

**Table 6: Annual cycle of the Chatham Rise hake stock assessment model from Holmes (2021), 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 | | | | | | | | | | |
| Sep | | X | X | | | | | | | Summer |
| Oct | | | | | | | | | | |
| Nov | | | | | | | | | | |
| Dec | 100 | | | X | 0.25 | 0.42 | X | | X | |
| Jan | | | | | | | | | | |
| Feb | | | | | | | | *Tangaroa* (26 @ 1992–2020) | X | |
| Mar | | | | | | | | | | Autumn |
| Apr | | | | | 0.50 | 0.25 | | | | |
| May | | | | | | | | | | |
| Jun | | | | | | | | | | Winter |
| Jul | | | | | 0.00 | 0.33 | | | | |
| Aug | | | | | | | | | | |
| Year end | | | | | | | | | | |
| Total | 100 | | | | 1.00 | 1.00 | | | | |

**Table 7: Assumed biological parameters for Sub-Antarctic hake.**

| Relationship | Reference | Parameter (units) | Value: Both | Male | Female |
|---|---|---|---|---|---|
| Natural mortality[1] | (Horn & Francis 2010) | $M$ (y$^{-1}$) | | 0.19 | 0.19 |
| von Bertalanffy growth | (Dunn et al. 2021a) | $t_0$ (y) | | -0.71 | -1.33 |
| | | $k$ (y$^{-1}$) | | 0.260 | 0.160 |
| | | $L_\infty$ (cm) | | 89.3 | 114.5 |
| | | CV | | 0.07 | 0.09 |
| Length-weight | (Dunn et al. 2021a) | a (g.cm$^{-1}$) | | 2.34e-6 | 1.86e-6 |
| | | b | | 3.258 | 3.310 |

| | | | |
|---|---|---|---|
| Stock recruitment relationship | | | |
| Stock recruitment steepness[2] | (Horn & Francis 2010) | $h$ | 0.8 |
| Recruitment variability[3] | | $\sigma_R$ | 1.1 |
| Ageing error | (Horn & Francis 2010) | CV | 0.08 |
| Proportion male at birth | | | 0.5 |
| Proportion of mature that spawn | | | 1.0 |
| Maximum exploitation rate[4] | (Dunn et al. 2021a) | $U_{max}$ | 0.7 |

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 8: Assumed biological parameters for the Chatham Rise hake.**

| Relationship | Reference | Parameter (units) | Value |
|---|---|---|---|
| Natural mortality | (Horn & Francis 2010) | $M$ ($y^{-1}$) | 0.19 |
| Schnute growth | (Holmes 2021) | $y_1$ | 24.5 |
| | | $y_2$ | 104.5 |
| | | $\tau_1$ | 1 |
| | | $\tau_2$ | 20 |
| | | $a$ | 0.131 |
| | | $b$ | 1.70 |
| | | $CV$ | 0.10 |
| Length-weight | (Holmes 2021) | a ($g.cm^{-1}$) | 2.0e-09 |
| | | b | 3.288 |
| Stock recruitment relationship | | | |
| Stock recruitment steepness | (Holmes 2021) | $h$ | 0.84 |
| Recruitment variability | | $\sigma_R$ | 1.1 |
| Ageing error | (Holmes 2021) | CV | 0.08 |
| Proportion of mature that spawn | | | 1.0 |
| Maximum exploitation rate | (Holmes 2021) | $U_{max}$ | 0.7 |

**Table 9: Maturity-at-age for males and females for Sub-Antarctic hake (Horn 2008) and unsexed for Chatham Rise hake (Holmes 2021).**

| Age | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15+ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Male | 0.01 | 0.03 | 0.09 | 0.22 | 0.46 | 0.71 | 0.88 | 0.96 | 0.98 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Female | 0.01 | 0.02 | 0.05 | 0.11 | 0.23 | 0.43 | 0.64 | 0.81 | 0.91 | 0.96 | 0.98 | 0.99 | 1.00 | 1.00 | 1.00 |
| Unsexed | 0.00 | 0.02 | 0.05 | 0.13 | 0.29 | 0.50 | 0.70 | 0.84 | 0.93 | 0.97 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 |

**Table 10: Summary of the Sub-Antarctic 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 Dunn et al. (2021a) and the models that were used as sensitivities in the management procedure (MP) evaluation (highlighted in grey).**

| Description | Model sensitivity | MP evaluation | $B_0$ | $B_{2024}$ (% $B_0$) |
|---|---|---|---|---|
| 2021 base | Yes | Yes | 59 000 (43 220–93 600) | 61.7 (49.5–75.1) |
| (a) Include September | Yes | No | 55 460 (41 900–84 910) | 59.8 (48.2–73.6) |
| (b) Remove age data (OBS) | Yes | No | 56 120 (41 490–91 960) | 61.9 (48.9–75.8) |
| (c) Remove AF data (+fixed YCS) | Yes | No | 46 600 (38 360–68 400) | 64.2 (49.5–81.1) |
| (d) Remove AF data (+TAN) | Yes | No | 41 470 (36 080–56 980) | 59.2 (43.1–77.7) |
| (e) CPUE CV = 0.2 (down weight surveys) | Yes | No | 53 400 (42 140–77 240) | 49.8 (41.8–59.5) |
| (f) Loose M Prior | Yes | No | 59 530 (43 190–100 120) | 61.8 (49.6–75.3) |
| (g) Fixed YCS | Yes | No | 41 420 (37 480–50 280) | 68.2 (58.1–78.7) |
| (h) Fixed M=0.15 $y^{-1}$ | Yes | Yes | 40 440 (36 050–46 170) | 51.9 (40.9–64.0) |
| (i) Fixed M=0.19 $y^{-1}$ | Yes | Yes | 54 000 (44 370–68 640) | 61.3 (49.8–75.0) |
| (j) Fixed M=0.23 $y^{-1}$ | Yes | Yes | 75 130 (55 310–110 190) | 68.6 (54.8–84.2) |
| (k) 2021 base (excluding AEX 1990 AFs) | Yes | No | 58 570 (43 150–91 100) | 61.5 (49.5–75.2) |

| | | |
|---|---|---|
| (l) Steepness h = 0.5 | Yes | Yes |
| (m) Steepness h = 0.66 | Yes | Yes |
| (n) Steepness h = 0.100 | Yes | Yes |

**Table 11: Summary of the Chatham Rise 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 Holmes (2021) and the models that were used as sensitivities in the management procedure (MP) evaluation (highlighted in grey).**

| Description | Model sensitivity | MP evaluation | $B_0$ | $B_{2024}$ (% $B_0$) |
|---|---|---|---|---|
| 2020 base | Yes | Yes | 32 838 (28 280–42 721) | 55.1 (45.7–65.9) |
| (a) Fixed M=0.15 $y^{-1}$ | Yes | Yes | 33 820 (28 550–36 560) | 48.4 (38.0–60.5) |
| (b) Fixed M=0.23 $y^{-1}$ | Yes | Yes | 36 300 (28 790–51 910) | 60.4 (47.5–75.4) |
| (c) CPUE-east run | Yes | No | 34 367 (29 504–44 113) | 58.0 (49.6–68.1) |
| (d) Steepness h = 0.5 | No | Yes | 33 570 (28 990–42 280) | 47.9 (37.8–60.5) |
| (e) Steepness h = 0.66 | No | Yes | 31 170 (27 380–40 000) | 50.0 (40.8–63.1) |
| (f) Steepness h = 0.100 | No | Yes | 31 790 (26 820–43 130) | 55.7 (43.7–69.8) |

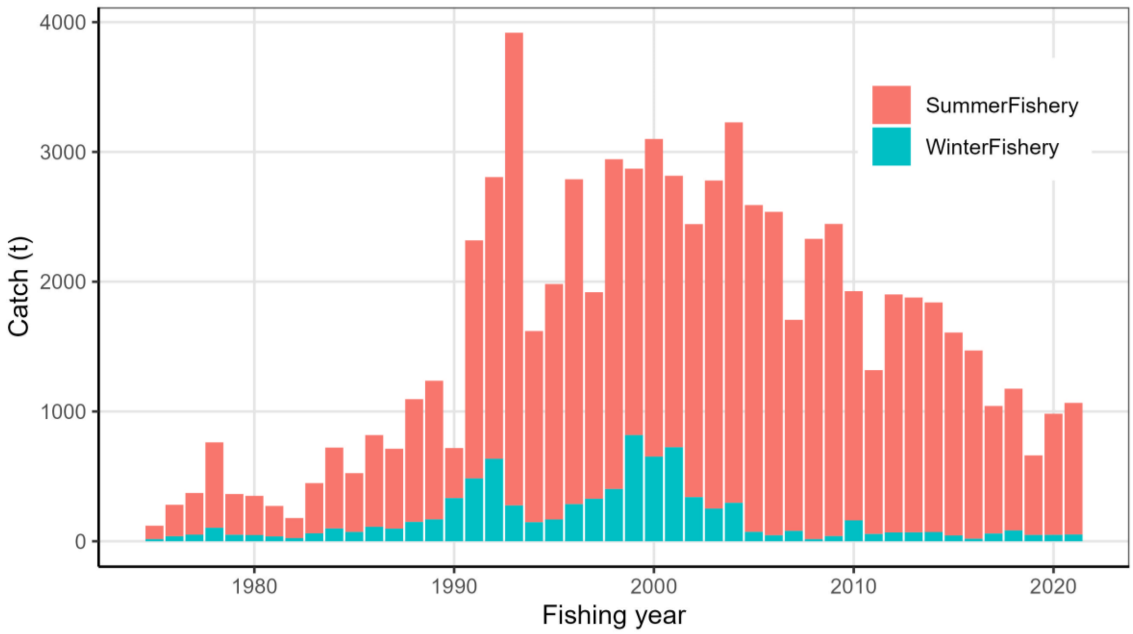


**Figure 7: Annual reported catch of Sub-Antarctic hake for the summer and winter fisheries for the fishing years 1975 (1974–75) to 2021 (2020–21) from Dunn et al. (2021b).**

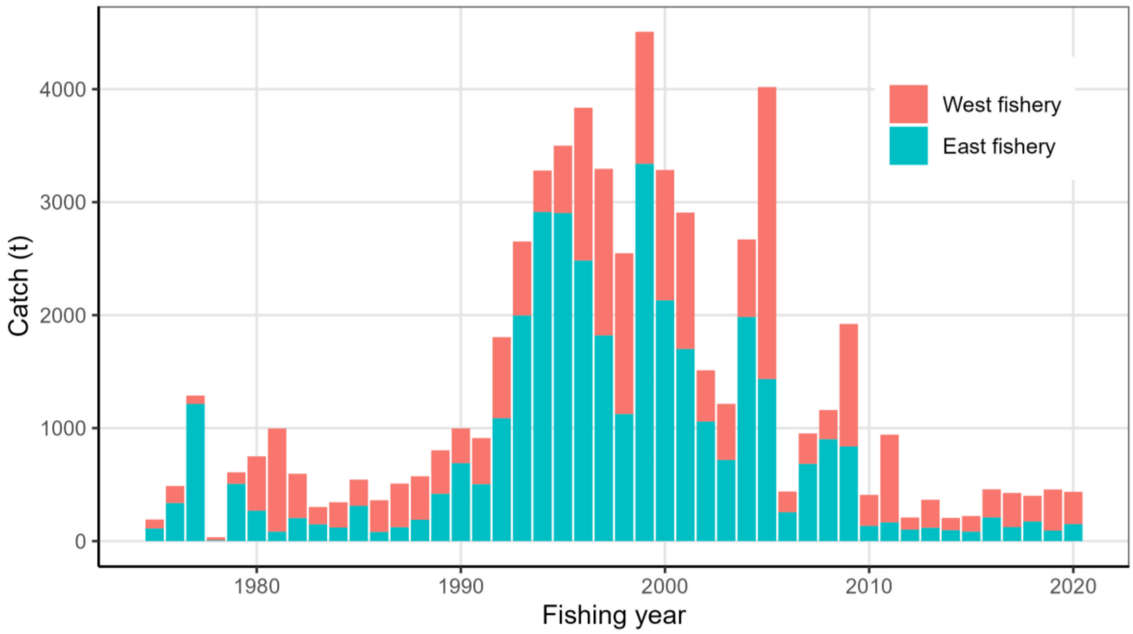


**Figure 8: Annual reported catch of Chatham Rise hake for the western and eastern fisheries for the fishing years 1975 (1974–75) to 2020 (2019–20) from Holmes (2021).**

### 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. For the Sub-Antarctic, the sampling error was assumed lognormally distributed with a CV=0.30 (see Figure 5 above) and CV=0.21 for the Chatham Rise (see Figure 6 above), based on the level of uncertainty associated with estimates of current stock status from the most recent stock assessments.

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 hake, 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 YCS from the last 10 years of estimated parameters from each assessment model. The periods were 2007–2016 for the Sub-Antarctic ($\mu$=0.74, Figure 9) and 2008–2017 for the Chartham Rise ($\mu$=0.75, Figure 10). These corresponded to the periods used for the projections in the assessment model as this was a period of lower than average recruitments for each stock.

The HCRs were also tested on the base case with an assumption that of 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 the Sub-Antarctic, these were then assumed to be the recruitments for the years after 2016, but with each iteration rescaled to have a mean equal to that for the recent period (2007–2016). For the Chatham Rise, these were recruitments after 2017 with each iteration rescaled to have a mean equal to that for the recent period (2008–2017). The resulting ARMA models are given in Figure 11 for the Sub-Antarctic and Figure 12 for the Chatham Rise. ARMA model estimates of the first-order autocorrelation are given for the Sub-Antarctic and Chatham Rise respectively in Figure 13 and Figure 14.

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 hake 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 ($\rho$=0) and assuming $\rho$=0.85, following Wiedenmann et al. (2015).

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).

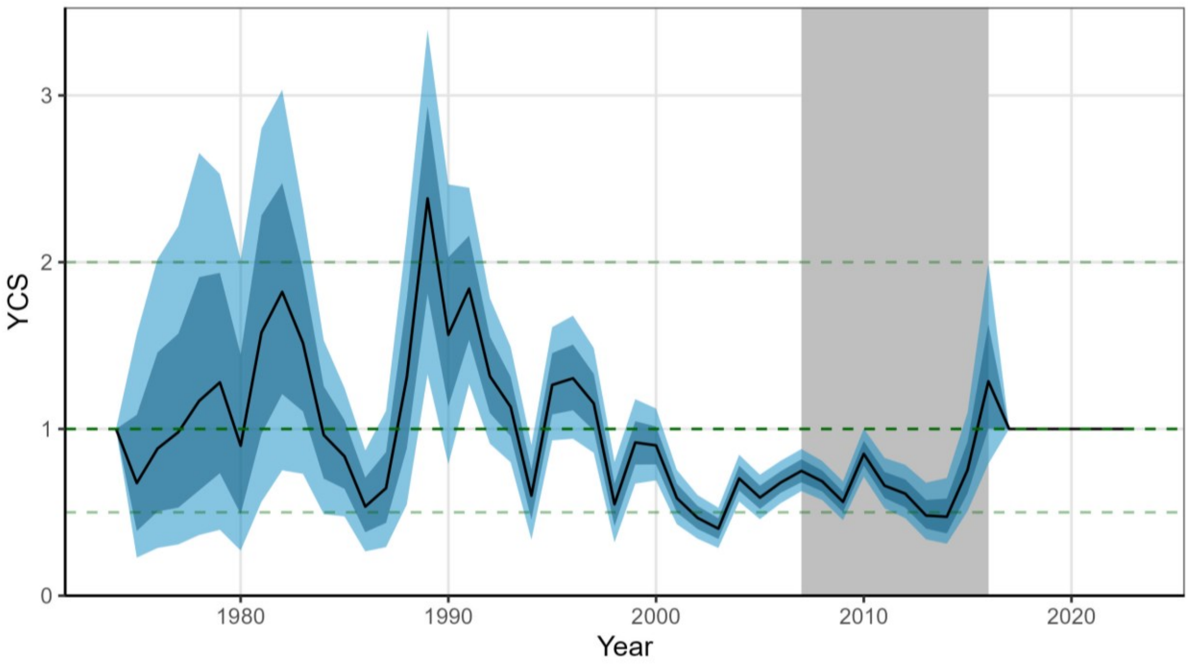


**Figure 9: Base case assessment model (Dunn et al. 2021b) posterior distribution of year class strengths (YCS) for years 1974–2021 (estimated for 1975–2016). The solid line indicates the median, dark blue shaded area the interquartile range, and the light blue shaded area the 95% CIs. The horizontal dashed green lines indicate the average of 0.5, 1, and 2 respectively. The period of recent YCS (2007–2016) is the period highlighted with the grey background.**

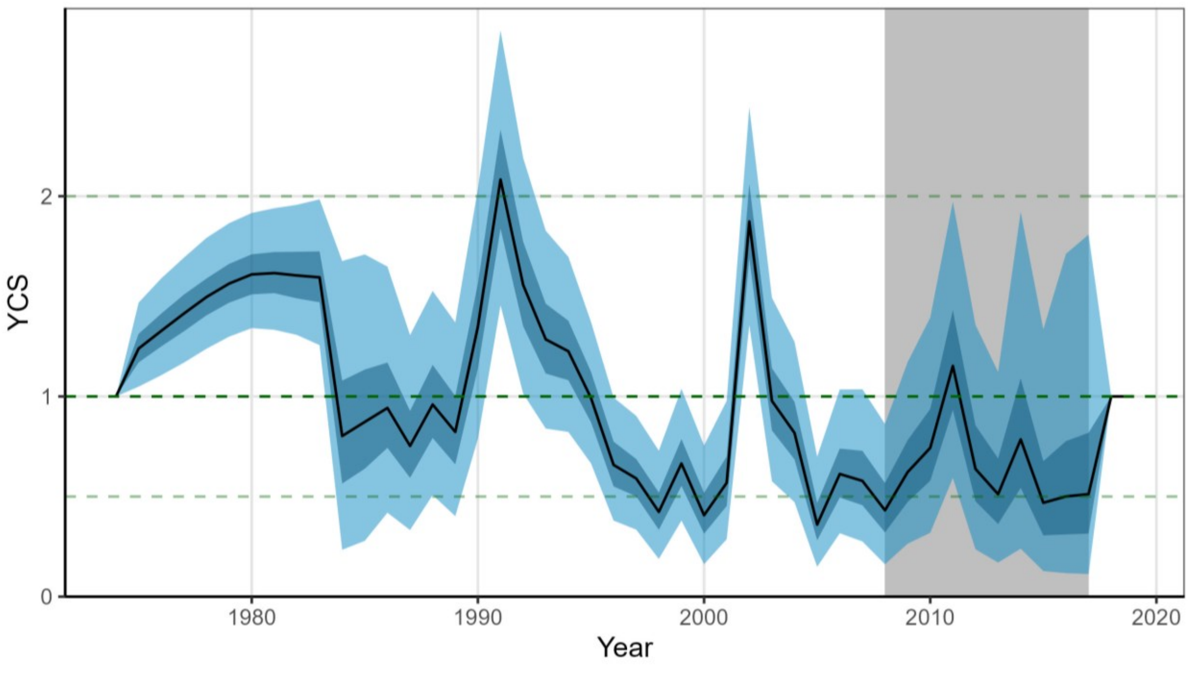


**Figure 10: Base case assessment model (Holmes 2021) posterior distribution of year class strengths (YCS) for years 1974–2020 (estimated for 1975–2017). The solid line indicates the median, dark blue shaded area the interquartile range, and the light blue shaded area the 95% CIs. The horizontal dashed green lines indicate the average of 0.5, 1, and 2 respectively. The period of recent YCS (2008–2017) is the period highlighted with the grey background.**

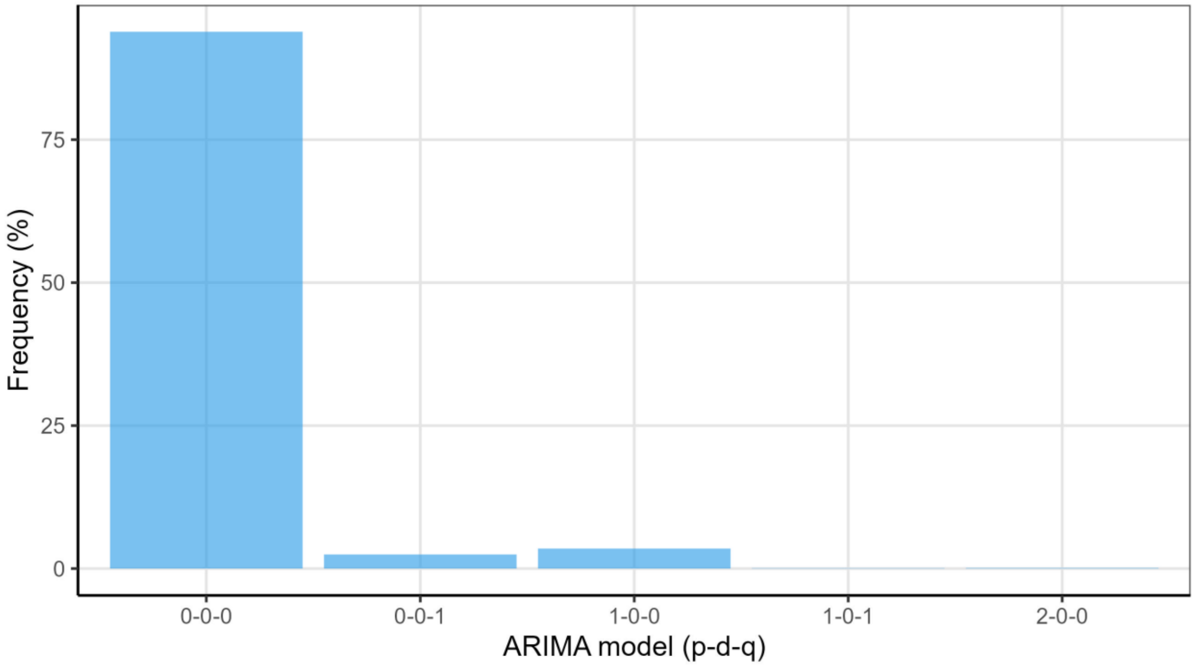


**Figure 11: Summary of estimated ARMA models (arima(*p*,*d*,*q*) with d=0) of the historical (1975–2016) YCS from the base case model (Dunn et al. 2021b) for Sub-Antarctic hake.**

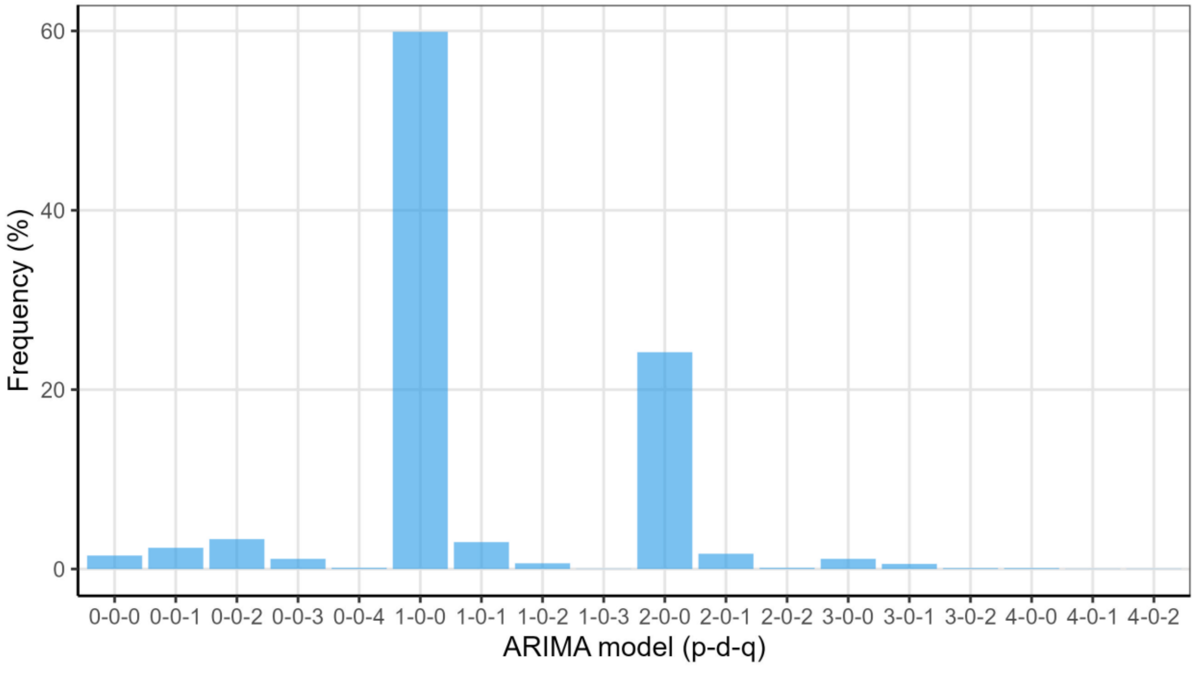


**Figure 12: Summary of estimated ARMA models (arima(*p*,*d*,*q*) with d=0) of the historical (1975–2017) YCS from the base case model (Holmes 2021) for Chatham Rise hake.**

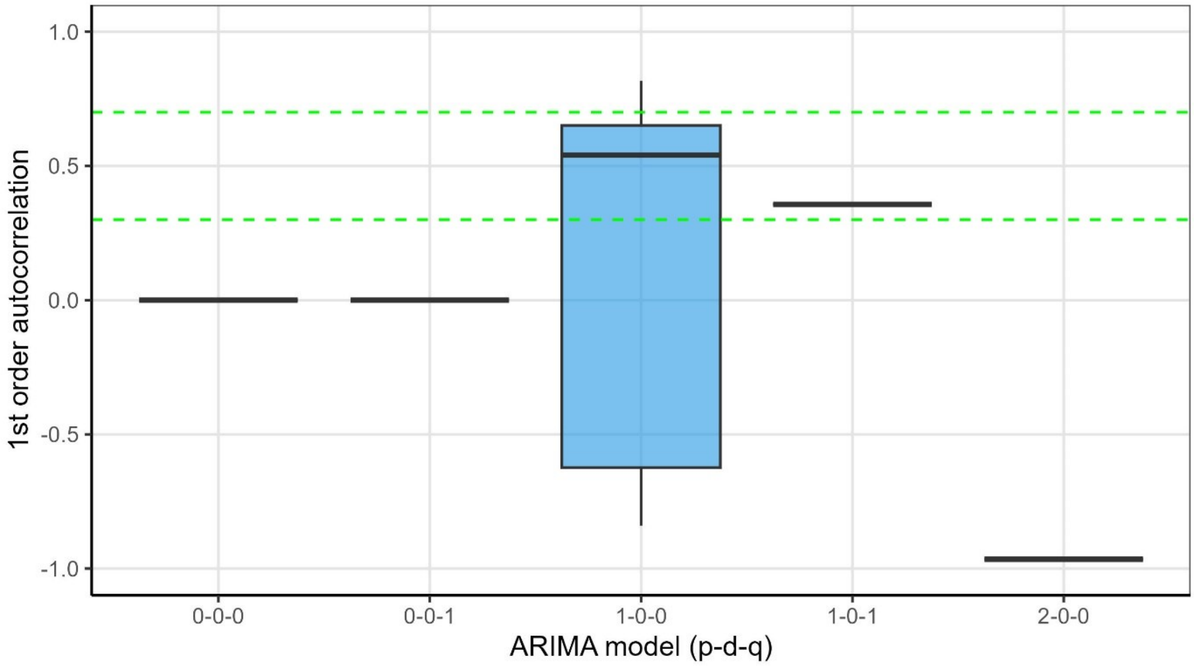


**Figure 13: Estimates of 1st order autocorrelation from the ARMA models (arima(*p,d,q*) with *d*=0) of the historical (1975–2016) YCS for the base case model (Dunn et al. 2021b) for Sub-Antarctic hake.**

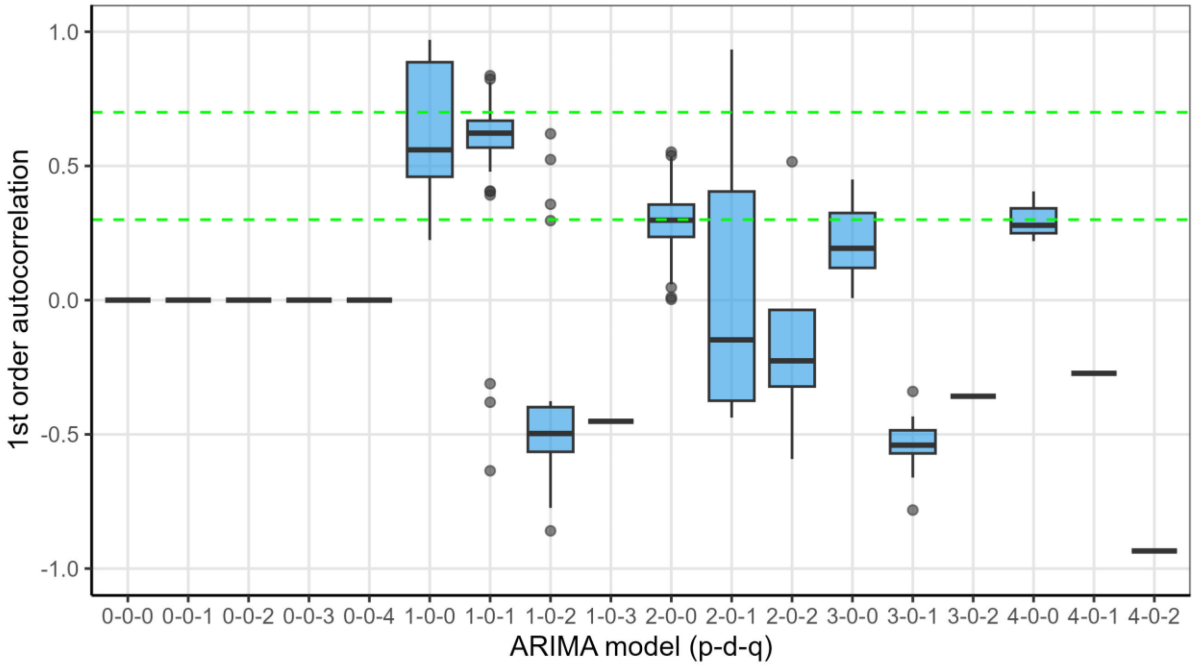


**Figure 14: Estimates of 1st order autocorrelation from the ARMA models (arima(*p,d,q*) with *d*=0) of the historical (1975–2017) YCS for the base case model (Holmes 2021) for Chatham Rise hake.**

# 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 18% $B_0$ ($U$=0.374) with a mean annual catch of 4640 t for the Sub-Antarctic and 17% $B_0$ ($U$=0.256) with a mean annual catch of 1420 t for the Chatham Rise.

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

The reference harvest rate ($U_{40\%B0}$) for each HCR is given in Table 12 for the Sub-Antarctic and Table 13 for the Chartham Rise. Long term projections for each HCR for the Sub-Antarctic and Chatham Rise stocks assuming recent YCS are given in Figure 15 and Figure 16 respectively. 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 0.10–0.12 for the Sub-Antarctic and 0.07–0.09 for the Chatham Rise stocks; 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 for the Sub-Antarctic are given in Figure 17. Current Sub-Antarctic catch limits are slightly 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 Sub-Antarctic stock of 62% (see Figure 17).

The expected long-term average and standard deviation of the catches for the Sub-Antarctic is shown in Table 12 with the distribution of expected SSB from the simulations in Figure 18. The probability of the Sub-Antarctic stock status being above 20% and 30% $B_0$ are shown in Figure 19 and Figure 20 respectively. For all HCRs, the probabilities of being above either 10% or 20% $B_0$ were all very high.

The estimated range of expected values of the Sub-Antarctic SSB (%$B_0$) under each HCR are given in Table 14. Expected stock status and quantiles, and the probability of being below 10% and 20% $B_0$ for each HCR are also given in Table 14. All rules had a negligible probability of being below either 10% or 20% $B_0$. The estimated interquartile range (Table 14) was between 34–47% $B_0$ for all the HCRS for the Sub-Antarctic, suggesting that the target range for the Sub-Antarctic stock could be defined as about 35–50 %$B_0$, with an associated probability of being inside the target range of about 50%.

The estimated catch limits (TACCs) that would be applied using the HCRs for the Chatham Rise are given in Figure 21. Current Chatham Rise catch limits are higher than that which would be expected from the application of the HCRs, given an estimate of the stock status (median SSB) for the Chatham Rise stock of 55% (see Figure 21).

The expected long-term average and standard deviation of the catches for the Chatham Rise are shown in Table 13 with the distribution of expected SSB from the simulations in Figure 22. The probability of the Chatham Rise stock status being above 20% and 30% $B_0$ are shown in Figure 23 and Figure 24 respectively. For all HCRs, the probabilities of being above either 10% or 20% $B_0$ were all very high.

The estimated range of expected values of the Chatham Rise SSB (%$B_0$) under each HCR are given in Table 15. Expected stock status and quantiles, and the probability of being below 10% and 20% $B_0$ for each HCR are also given in Table 15. All rules had a negligible probability of being below either 10% or 20% $B_0$. The estimated interquartile range (Table 15) was between 34–47% $B_0$ for all the HCRS for the Chatham Rise, suggesting that the target range for the Chatham Rise stock could be defined as about 35–50 %$B_0$, with an associated probability of being inside the target range of about 50%.

**Table 12: Estimated values of the Sub-Antarctic reference harvest rate $U_{40\%B0}$ and the expected long term average and standard deviation of the catch (E(catch) and sd(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 | | $U_{40\%B0}$ | E(catch) | sd(catch) |
|---|---|---|---|---|---|---|---|
| | Type | Label | Min. Λ (%) | Max. Λ (%) | | | |
| Rule-1 | Constant | Rule-1.1 | 0 | – | 0.108 | 2 734 | 1 250 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Rule-1.2 | 10 | – | 0.108 | 2 732 | 1 249 |
| | | Rule-1.3 | 0 | 20 | 0.115 | 2 720 | 961 |
| | | Rule-1.4 | 10 | 20 | 0.115 | 2 717 | 959 |
| Rule-2 | Ramp (rTh=0.0) | Rule-2.1 | 0 | – | 0.120 | 2 736 | 1 545 |
| | | Rule-2.2 | 10 | – | 0.120 | 2 735 | 1 544 |
| | | Rule-2.3 | 0 | 20 | 0.131 | 2 714 | 1 087 |
| | | Rule-2.4 | 10 | 20 | 0.131 | 2 712 | 1 082 |
| Rule-3 | Ramp (rTh=0.1) | Rule-3.1 | 0 | – | 0.124 | 2 737 | 1 674 |
| | | Rule-3.2 | 10 | – | 0.124 | 2 737 | 1 674 |
| | | Rule-3.3 | 0 | 20 | 0.136 | 2 707 | 1 129 |
| | | Rule-3.4 | 10 | 20 | 0.136 | 2 708 | 1 129 |
| Rule-4 | Ramp (rTh=0.2) | Rule-4.1 | 0 | – | 0.116 | 2 737 | 1 496 |
| | | Rule-4.2 | 10 | – | 0.116 | 2 737 | 1 497 |
| | | Rule-4.3 | 0 | 20 | 0.124 | 2 714 | 1 053 |
| | | Rule-4.4 | 10 | 20 | 0.124 | 2 711 | 1 049 |

**Table 13: Estimated values of the Chatham Rise reference harvest rate $U_{40\%B0}$ and the expected long term average and standard deviation of the catch (E(catch) and sd(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 | | $U_{40\%B0}$ | E(catch) | sd(catch) |
|---|---|---|---|---|---|---|---|
| | Type | Label | Min. Λ (%) | Max. Λ (%) | | | |
| Rule-1 | Constant | Rule-1.1 | 0 | – | 0.072 | 954 | 355 |
| | | Rule-1.2 | 10 | – | 0.072 | 950 | 354 |
| | | Rule-1.3 | 0 | 20 | 0.074 | 952 | 307 |
| | | Rule-1.4 | 10 | 20 | 0.074 | 952 | 306 |
| Rule-2 | Ramp (rTh=0.0) | Rule-2.1 | 0 | – | 0.080 | 963 | 438 |
| | | Rule-2.2 | 10 | – | 0.079 | 963 | 438 |
| | | Rule-2.3 | 0 | 20 | 0.084 | 964 | 360 |
| | | Rule-2.4 | 10 | 20 | 0.084 | 964 | 359 |
| Rule-3 | Ramp (rTh=0.1) | Rule-3.1 | 0 | – | 0.083 | 968 | 474 |
| | | Rule-3.2 | 10 | – | 0.082 | 968 | 474 |
| | | Rule-3.3 | 0 | 20 | 0.088 | 966 | 379 |
| | | Rule-3.4 | 10 | 20 | 0.088 | 967 | 378 |
| Rule-4 | Ramp (rTh=0.2) | Rule-4.1 | 0 | – | 0.076 | 961 | 413 |
| | | Rule-4.2 | 10 | – | 0.076 | 959 | 412 |
| | | Rule-4.3 | 0 | 20 | 0.079 | 959 | 340 |
| | | Rule-4.4 | 10 | 20 | 0.079 | 961 | 340 |

**Table 14: Estimated values of the Sub-Antarctic reference harvest rate $U_{40\%B0}$, the expected mean, 25–75% quantiles, and probability of being above 10% and 20% *B*0 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 | 0.072 | 40.6 | 34.6–45.9 | 1.000 | 0.998 |
| Rule-1.2 | 0.072 | 40.7 | 34.6–45.9 | 1.000 | 0.998 |
| Rule-1.3 | 0.074 | 40.7 | 34.4–46.2 | 1.000 | 0.996 |
| Rule-1.4 | 0.074 | 40.8 | 34.5–46.3 | 1.000 | 0.996 |
| Rule-2.1 | 0.080 | 40.6 | 34.7–45.9 | 1.000 | 0.997 |
| Rule-2.2 | 0.079 | 40.6 | 34.7–46.0 | 1.000 | 0.997 |
| Rule-2.3 | 0.084 | 40.8 | 34.4–46.5 | 1.000 | 0.993 |
| Rule-2.4 | 0.084 | 40.8 | 34.4–46.5 | 1.000 | 0.993 |
| Rule-3.1 | 0.083 | 40.6 | 34.6–46.0 | 1.000 | 0.997 |
| Rule-3.2 | 0.082 | 40.6 | 34.6–46.0 | 1.000 | 0.997 |
| Rule-3.3 | 0.088 | 40.9 | 34.2–46.8 | 1.000 | 0.992 |

| | | | | | |
|---|---|---|---|---|---|
| Rule-3.4 | 0.088 | 40.8 | 34.3–46.8 | 1.000 | 0.992 |
| Rule-4.1 | 0.076 | 40.6 | 34.7–45.9 | 1.000 | 0.998 |
| Rule-4.2 | 0.076 | 40.6 | 34.7–45.9 | 1.000 | 0.998 |
| Rule-4.3 | 0.079 | 40.8 | 34.4–46.4 | 1.000 | 0.995 |
| Rule-4.4 | 0.079 | 40.9 | 34.5–46.5 | 1.000 | 0.995 |

**Table 15: Estimated values of the Chatham Rise 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 | 0.072 | 40.9 | 34.1–46.8 | 1.000 | 0.996 |
| Rule-1.2 | 0.072 | 41.0 | 34.2–47.0 | 1.000 | 0.996 |
| Rule-1.3 | 0.074 | 40.9 | 33.9–47.0 | 1.000 | 0.994 |
| Rule-1.4 | 0.074 | 40.9 | 33.9–47.0 | 1.000 | 0.994 |
| Rule-2.1 | 0.080 | 40.6 | 34.3–46.1 | 1.000 | 0.998 |
| Rule-2.2 | 0.079 | 40.6 | 34.3–46.1 | 1.000 | 0.998 |
| Rule-2.3 | 0.084 | 40.5 | 33.8–46.3 | 1.000 | 0.994 |
| Rule-2.4 | 0.084 | 40.5 | 33.8–46.3 | 1.000 | 0.994 |
| Rule-3.1 | 0.083 | 40.5 | 34.2–45.9 | 1.000 | 0.998 |
| Rule-3.2 | 0.082 | 40.5 | 34.2–45.9 | 1.000 | 0.998 |
| Rule-3.3 | 0.088 | 40.4 | 33.7–46.1 | 1.000 | 0.994 |
| Rule-3.4 | 0.088 | 40.4 | 33.7–46.1 | 1.000 | 0.993 |
| Rule-4.1 | 0.076 | 40.7 | 34.2–46.3 | 1.000 | 0.998 |
| Rule-4.2 | 0.076 | 40.8 | 34.3–46.3 | 1.000 | 0.998 |
| Rule-4.3 | 0.079 | 40.7 | 33.9–46.5 | 1.000 | 0.994 |
| Rule-4.4 | 0.079 | 40.7 | 33.9–46.5 | 1.000 | 0.994 |

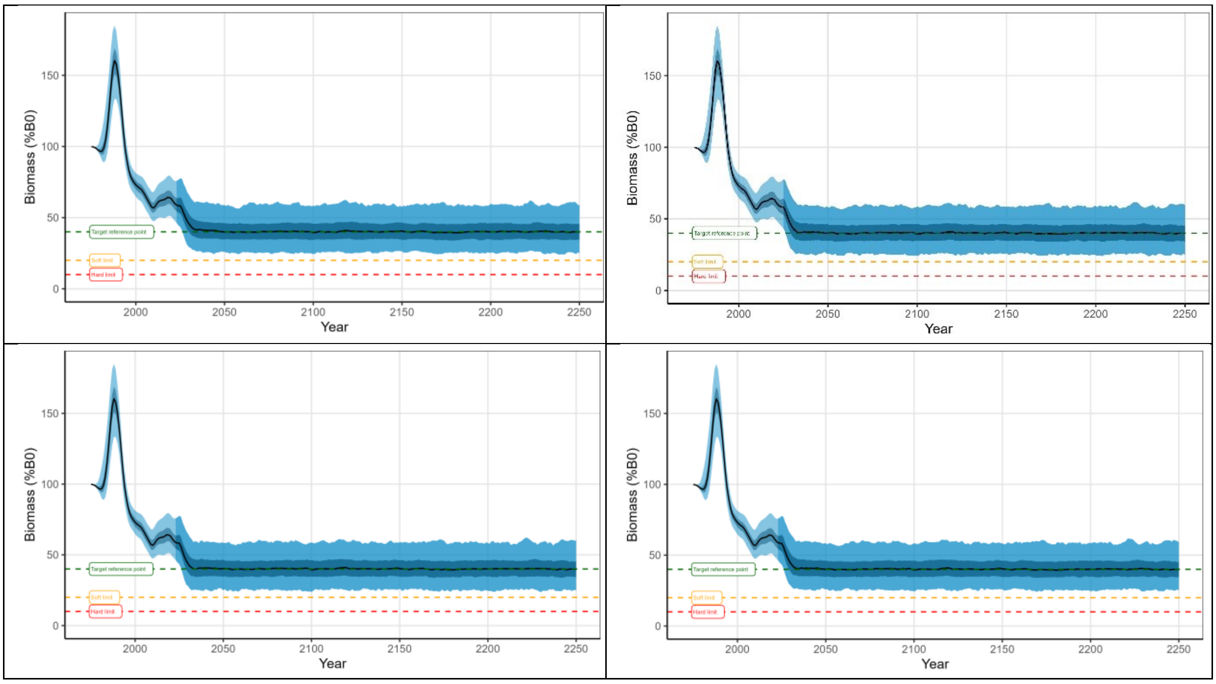

**Figure 15: Simulated SSB (%$B_0$) trends from the Sub-Antarctic base case assessment from Dunn et al. (2021b) using four candidate Harvest Control Rules, Rule-1.1 (top left), Rule-2.1 (top right), Rule-3.1 (bottom left), and Rule-4.1 (bottom right). The solid line indicates the median, dark shaded 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.**

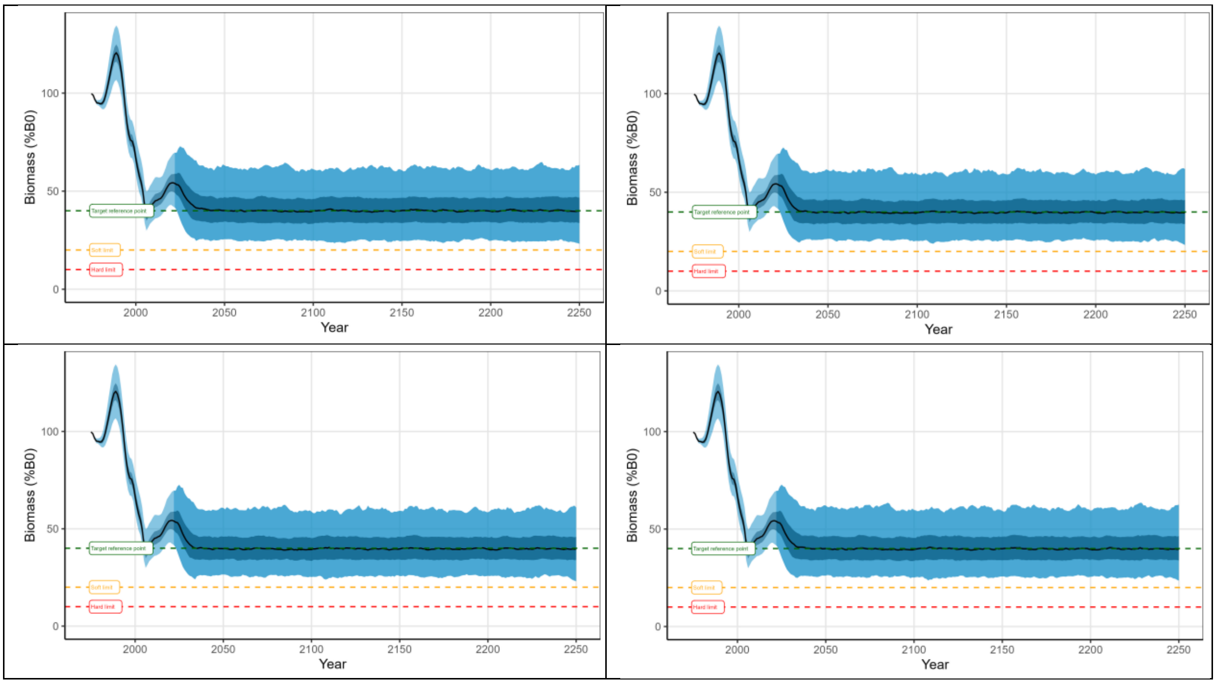


**Figure 16: Simulated SSB (%$B_0$) trends from the Chatham Rise base case assessment from Dunn et al. (2021b) using four candidate Harvest Control Rules, Rule-1.1 (top left), Rule-2.1 (top right), Rule-3.1 (bottom left), and Rule-4.1 (bottom right). The solid line indicates the median, dark shaded area 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.**

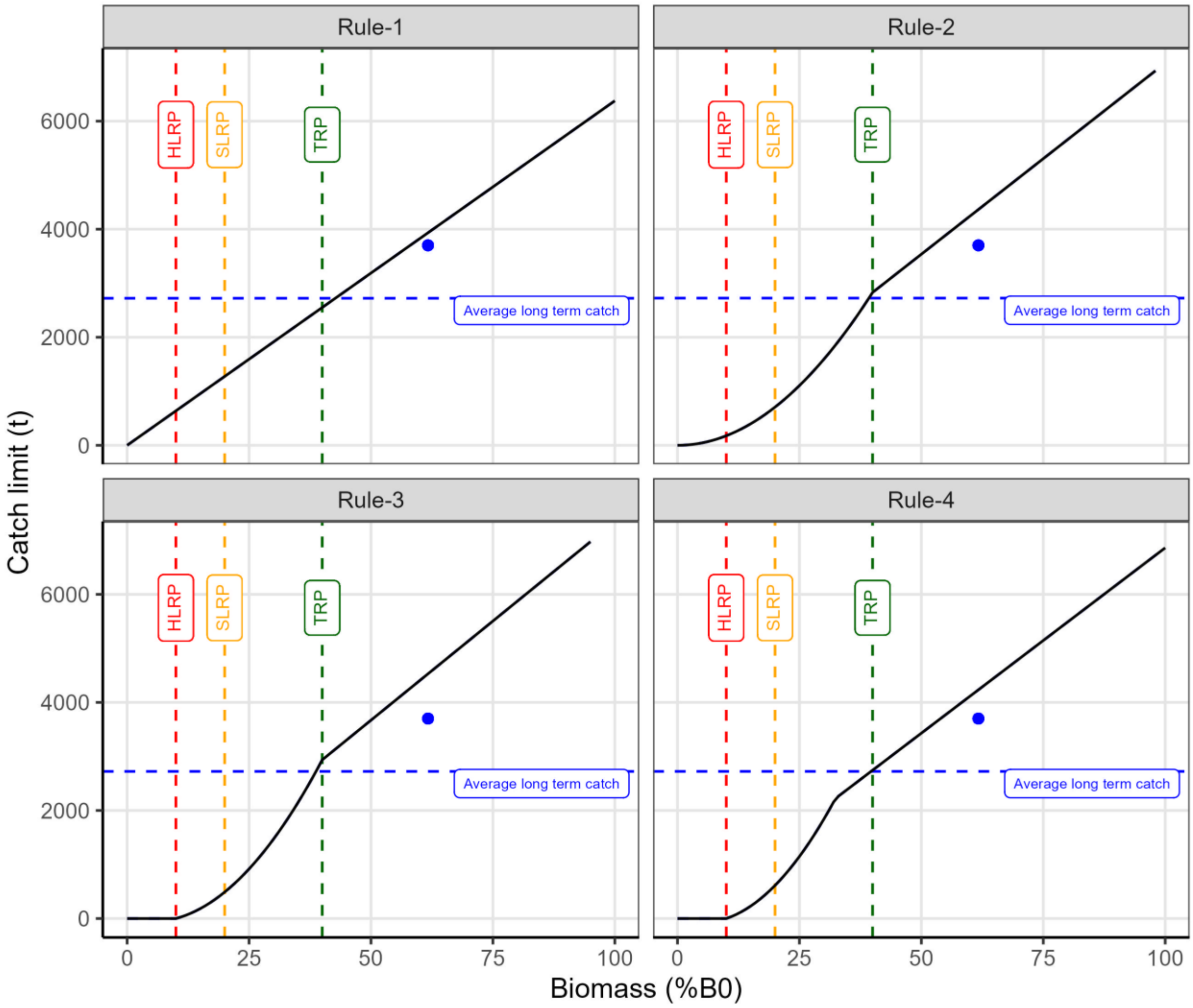


**Figure 17: Expected catch limits for the Sub-Antarctic from the candidate Harvest Control Rules (HCRs). The black line gives the catch limit for the estimated SSB/*B*0 ratio, the horizontal blue dashed line gives the average expected long term average catch under the HCR, and the blue point indicates the current catch limit for the current (2021) estimated SSB using the 2021 base case model and recent recruitment. Vertical lines indicate the target (green, 40% $B_0$), soft (orange, 20% $B_0$), and hard (red, 10% $B_0$) limits respectively.**

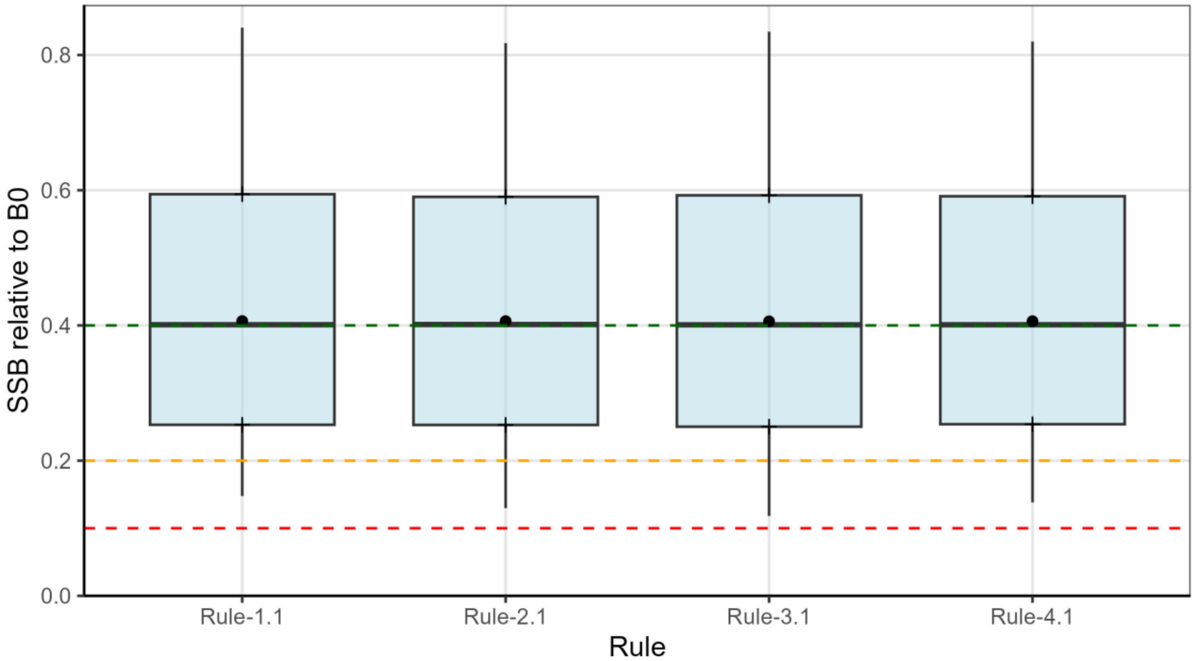


**Figure 18: Distribution of the Sub-Antarctic estimated biomass (%SSB) (performance indicator P02) using the reference $U_{40\%B0}$ for each candidate HCR with the base case model with non-constrained catch for Rule-1, Rule-2, Rule-3, and Rule-4. Boxes indicate the 80% quantiles, the horizontal tick 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.**

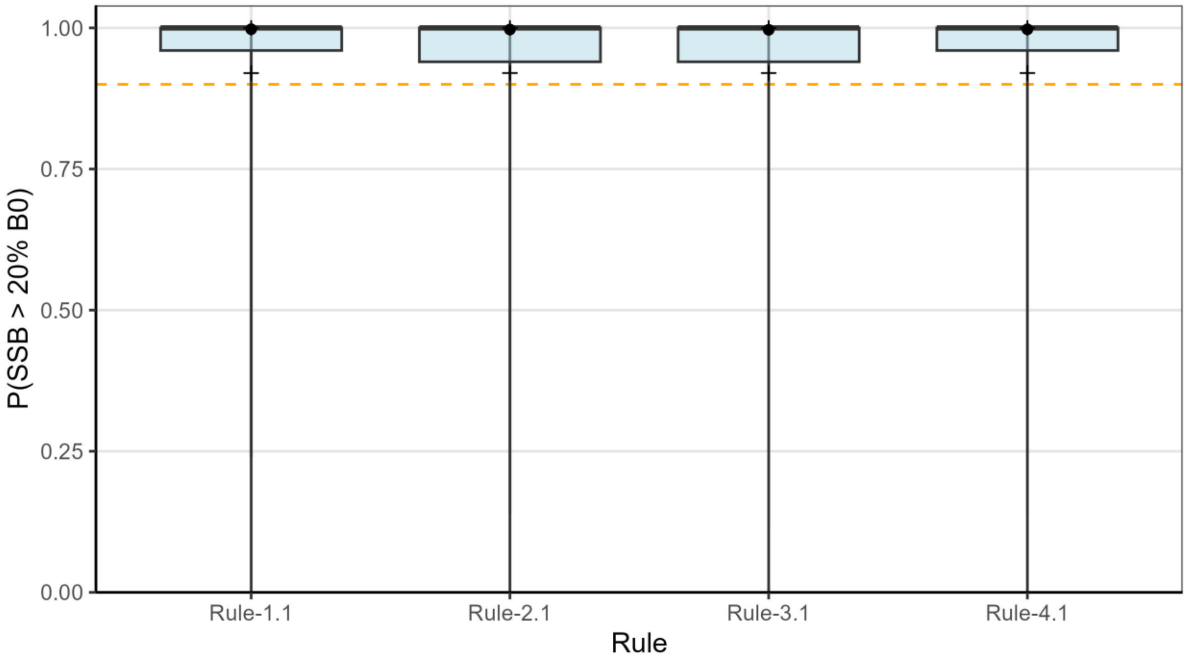


**Figure 19: Distribution of the Sub-Antarctic probability of being below the soft limit ($LRP_S$) (performance indicator P04) using the reference $U_{40\%B0}$ for each candidate HCR with the base case model with non-constrained catch for Rule-1, Rule-2, Rule-3, and Rule-4. Boxes indicate the 80% quantiles, 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. The orange horizontal dashed line indicates a 10% probability of being below the soft limit.**

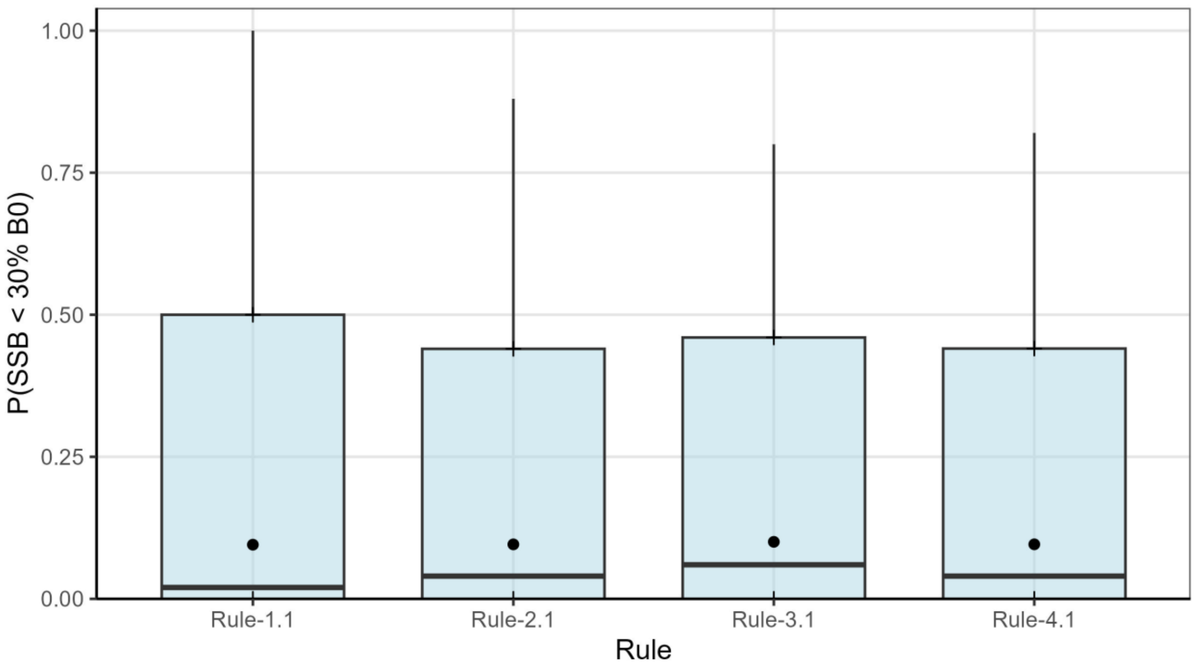


**Figure 20: Distribution of the Sub-Antarctic probability of being below 30% $B_0$ (performance indicator P05) using the reference $U_{40\%B0}$ for each candidate HCR with the base case model with a non-constrained catch for Rule-1, Rule-2, Rule-3, and Rule-4. Boxes indicate the 80% quantiles, the horizontal 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.**

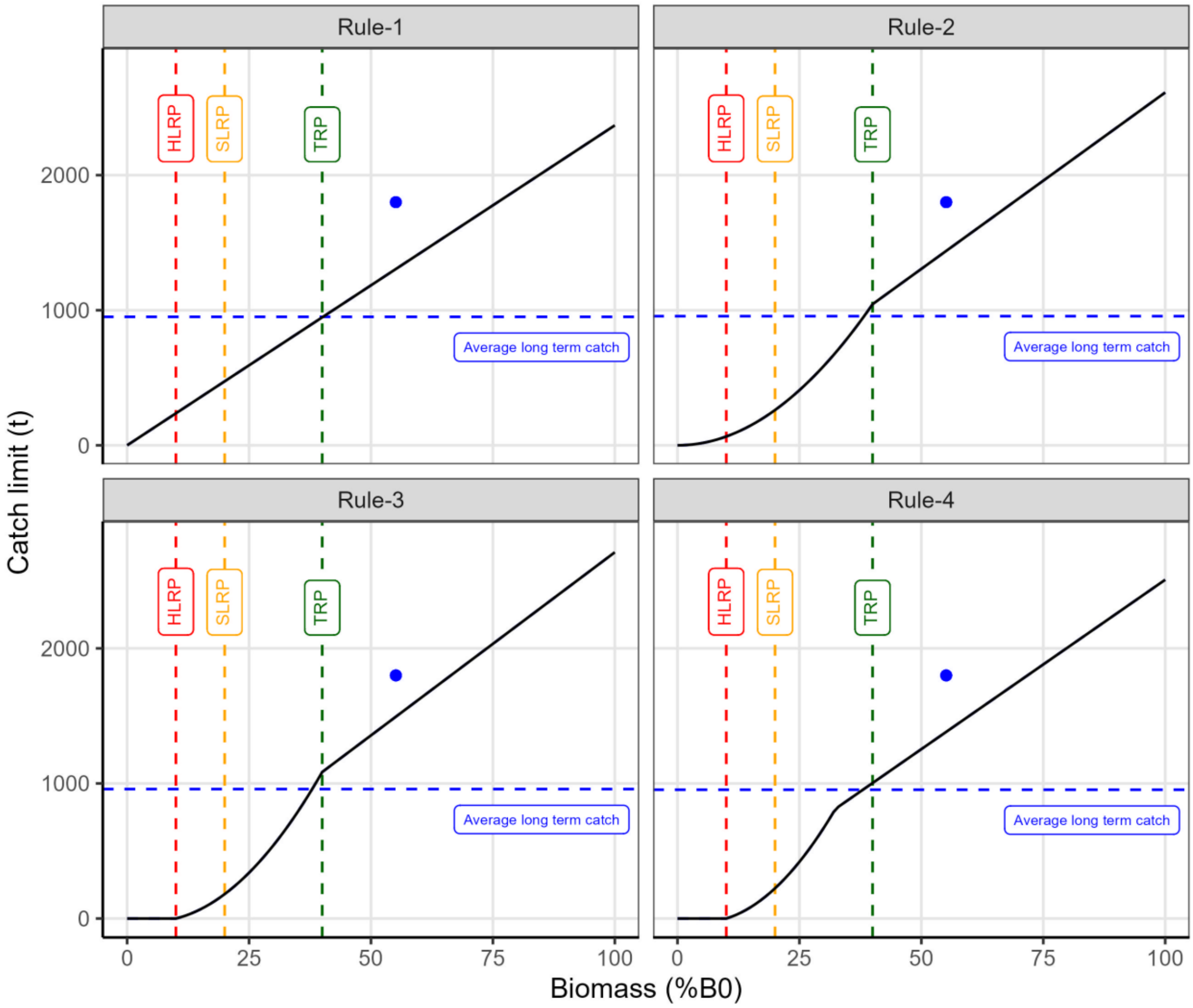


**Figure 21: Expected catch limits for the Chatham Rise from the candidate Harvest Control Rules (HCRs). The black line gives the catch limit for the estimated SSB/*B*0 ratio, the horizontal blue dashed line gives the average expected long term average catch under the HCR, and the blue point indicates the current catch limit for the current (2020) estimated SSB using the 2020 base case model and recent recruitment. Vertical lines indicate the target (green, 40% $B_0$), soft (orange, 20% $B_0$), and hard (red, 10% $B_0$) limits respectively.**

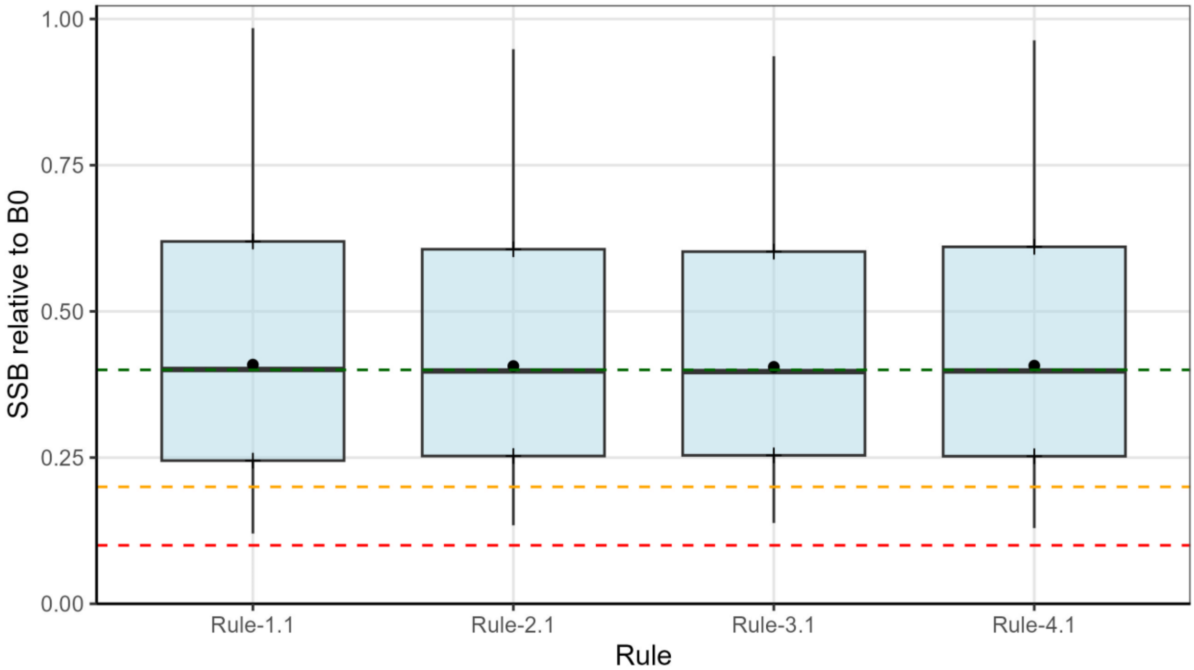


**Figure 22: Distribution of the Chatham Rise estimated biomass (%SSB) (performance indicator P02) using the reference $U_{40\%B0}$ for each candidate HCR with the base case model with non-constrained catch for Rule-1, Rule-2, Rule-3, and Rule-4. Boxes indicate the 80% quantiles, the horizontal tick 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.**

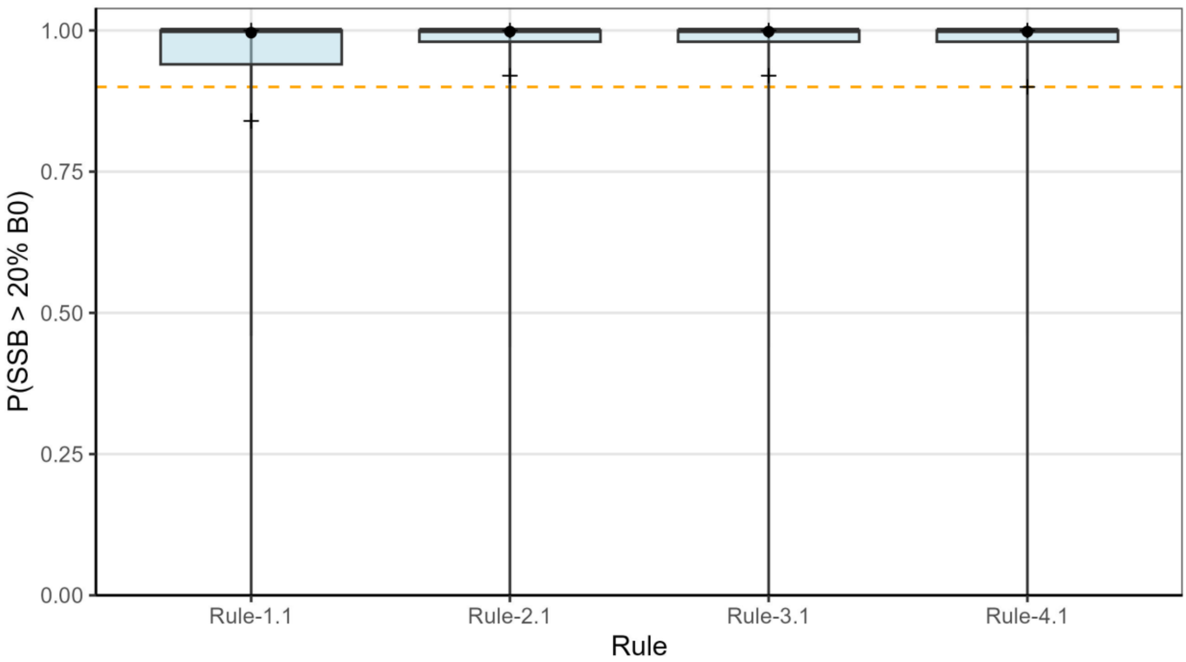


**Figure 23: Distribution of the Chatham Rise probability of being below the soft limit ($LRP_S$) (performance indicator P04) using the reference $U_{40\%B0}$ for each candidate HCR with the base case model with non-constrained catch for Rule-1, Rule-2, Rule-3, and Rule-4. Boxes indicate the 80% quantiles, 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. The orange horizontal dashed line indicates a 10% probability of being below the soft limit.**

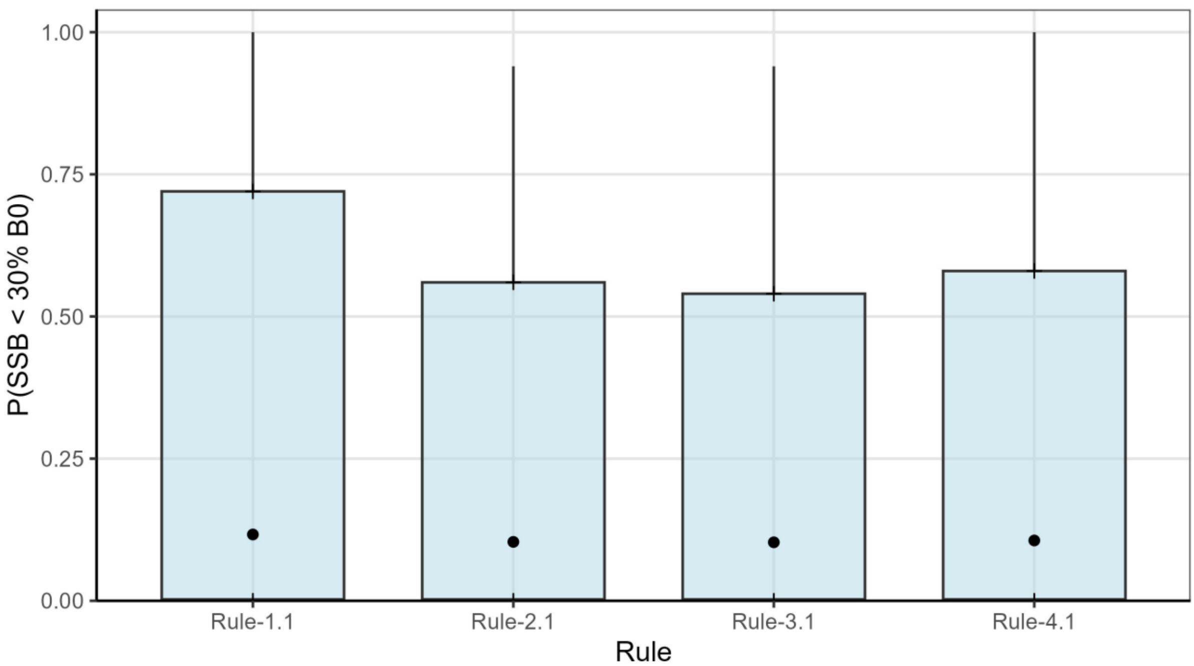


**Figure 24: Distribution of the Chatham Rise probability of being below 30% $B_0$ (performance indicator P05) using the reference $U_{40\%B0}$ for each candidate HCR with the base case model with a non-constrained catch for Rule-1, Rule-2, Rule-3, and Rule-4. Boxes indicate the 80% quantiles, the horizontal 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 both the Sub-Antarctic and Chatham Rise models 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 recent period (either 2007–2016 for the Sub-Antarctic or 2008–2017 for the Chatham Rise) (arimaYCS, see Figure 11 and Figure 12 above), (iii) assuming a between-assessment autocorrelation of $\rho$=0.8 (rho), and (iv) assuming both autocorrelation in year classes using the ARMA process in (ii), as well as between-assessment autocorrelation of $\rho$=0.8 (arimaYCS_rho).

For the Sub-Antarctic, 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 16. 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 17 and Table 18 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 19, with the standard deviations (C02) in Table 20. The proportion of years where a catch limit change takes place (C03) is given in Table 21.

For the Chatham Rise, 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 22. 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 23 and Table 24 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 25, with the standard deviations (C02) in Table 26. The proportion of years where a catch limit change takes place (C03) is given in Table 27.

**Table 16: Expected (mean) values for the Sub-Antarctic 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 | 40.6 | 56.2 | 40.0 | 40.7 | 39.9 |
| Rule-1.2 | 40.7 | 56.2 | 40.0 | 40.6 | 39.8 |
| Rule-1.3 | 40.7 | 57.1 | 40.0 | 39.4 | 38.6 |
| Rule-1.4 | 40.8 | 57.1 | 40.1 | 39.4 | 38.6 |
| Rule-2.1 | 40.6 | 54.6 | 40.0 | 38.6 | 37.8 |
| Rule-2.2 | 40.6 | 54.5 | 40.0 | 38.4 | 37.7 |
| Rule-2.3 | 40.8 | 55.2 | 40.2 | 36.8 | 36.1 |
| Rule-2.4 | 40.8 | 55.2 | 40.2 | 36.7 | 35.9 |
| Rule-3.1 | 40.6 | 54.0 | 40.0 | 37.8 | 37.1 |
| Rule-3.2 | 40.6 | 54.0 | 40.0 | 37.7 | 37.0 |
| Rule-3.3 | 40.9 | 54.7 | 40.3 | 35.9 | 35.2 |
| Rule-3.4 | 40.8 | 54.6 | 40.2 | 35.8 | 35.1 |
| Rule-4.1 | 40.6 | 54.9 | 40.0 | 39.2 | 38.4 |
| Rule-4.2 | 40.6 | 54.9 | 40.0 | 39.1 | 38.3 |
| Rule-4.3 | 40.8 | 55.9 | 40.2 | 37.9 | 37.2 |
| Rule-4.4 | 40.9 | 56.0 | 40.2 | 37.9 | 37.1 |

**Table 17: Estimated values for the Sub-Antarctic 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 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 |
| Rule-1.2 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 |
| Rule-1.3 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 |
| Rule-1.4 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 |
| Rule-2.1 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 |
| Rule-2.2 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 |
| Rule-2.3 | 1.00 | 1.00 | 0.99 | 1.00 | 0.97 |
| Rule-2.4 | 1.00 | 1.00 | 1.00 | 1.00 | 0.97 |
| Rule-3.1 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 |
| Rule-3.2 | 1.00 | 1.00 | 1.00 | 1.00 | 0.97 |
| Rule-3.3 | 1.00 | 1.00 | 0.99 | 1.00 | 0.97 |
| Rule-3.4 | 1.00 | 1.00 | 0.99 | 1.00 | 0.96 |
| Rule-4.1 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 |
| Rule-4.2 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 |
| Rule-4.3 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 |
| Rule-4.4 | 1.00 | 1.00 | 1.00 | 1.00 | 0.97 |

**Table 18: Estimated values for the Sub-Antarctic 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 | 1.00 | 1.00 | 0.99 | 0.99 | 0.99 |
| Rule-1.2 | 1.00 | 1.00 | 0.99 | 0.99 | 0.99 |
| Rule-1.3 | 1.00 | 1.00 | 0.99 | 0.99 | 0.99 |
| Rule-1.4 | 1.00 | 1.00 | 0.99 | 0.99 | 0.98 |
| Rule-2.1 | 1.00 | 1.00 | 1.00 | 0.99 | 0.98 |
| Rule-2.2 | 1.00 | 1.00 | 1.00 | 0.99 | 0.98 |
| Rule-2.3 | 0.99 | 0.99 | 0.99 | 0.98 | 0.97 |
| Rule-2.4 | 0.99 | 0.99 | 0.99 | 0.98 | 0.97 |
| Rule-3.1 | 1.00 | 1.00 | 0.99 | 0.99 | 0.98 |
| Rule-3.2 | 1.00 | 1.00 | 0.99 | 0.98 | 0.98 |
| Rule-3.3 | 0.99 | 0.99 | 0.99 | 0.98 | 0.97 |
| Rule-3.4 | 0.99 | 0.99 | 0.99 | 0.97 | 0.96 |
| Rule-4.1 | 1.00 | 1.00 | 1.00 | 0.99 | 0.99 |
| Rule-4.2 | 1.00 | 1.00 | 1.00 | 0.99 | 0.98 |
| Rule-4.3 | 0.99 | 1.00 | 0.99 | 0.99 | 0.98 |
| Rule-4.4 | 0.99 | 1.00 | 0.99 | 0.98 | 0.98 |

**Table 19: Estimated values for the Sub-Antarctic 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 | 2 734 | 3 764 | 2 679 | 2 725 | 2 673 |
| Rule-1.2 | 2 732 | 3 762 | 2 678 | 2 726 | 2 678 |
| Rule-1.3 | 2 720 | 3 662 | 2 671 | 2 810 | 2 755 |
| Rule-1.4 | 2 717 | 3 657 | 2 668 | 2 808 | 2 754 |
| Rule-2.1 | 2 736 | 3 886 | 2 676 | 2 867 | 2 811 |
| Rule-2.2 | 2 735 | 3 886 | 2 676 | 2 871 | 2 815 |
| Rule-2.3 | 2 714 | 3 789 | 2 660 | 2 983 | 2 924 |

| | | | | | |
|---|---|---|---|---|---|
| Rule-2.4 | 2 712 | 3 787 | 2 657 | 2 983 | 2 925 |
| Rule-3.1 | 2 737 | 3 926 | 2 676 | 2 917 | 2 859 |
| Rule-3.2 | 2 737 | 3 927 | 2 675 | 2 921 | 2 862 |
| Rule-3.3 | 2 707 | 3 824 | 2 648 | 3 036 | 2 975 |
| Rule-3.4 | 2 708 | 3 826 | 2 648 | 3 041 | 2 978 |
| Rule-4.1 | 2 737 | 3 857 | 2 680 | 2 826 | 2 770 |
| Rule-4.2 | 2 737 | 3 858 | 2 680 | 2 829 | 2 775 |
| Rule-4.3 | 2 714 | 3 749 | 2 663 | 2 912 | 2 855 |
| Rule-4.4 | 2 711 | 3 741 | 2 661 | 2 909 | 2 851 |

**Table 20: Estimated standard deviation for the Sub-Antarctic 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 | 1 250 | 1 986 | 1 206 | 809 | 786 |
| Rule-1.2 | 1 249 | 1 983 | 1 205 | 813 | 793 |
| Rule-1.3 | 961 | 1 386 | 921 | 841 | 821 |
| Rule-1.4 | 959 | 1 379 | 918 | 846 | 826 |
| Rule-2.1 | 1 545 | 2 278 | 1 501 | 862 | 839 |
| Rule-2.2 | 1 544 | 2 277 | 1 501 | 869 | 849 |
| Rule-2.3 | 1 087 | 1 535 | 1 035 | 907 | 885 |
| Rule-2.4 | 1 082 | 1 530 | 1 035 | 912 | 892 |
| Rule-3.1 | 1 674 | 2 400 | 1 631 | 881 | 860 |
| Rule-3.2 | 1 674 | 2 401 | 1 629 | 888 | 871 |
| Rule-3.3 | 1 129 | 1 588 | 1 078 | 928 | 907 |
| Rule-3.4 | 1 129 | 1 586 | 1 079 | 936 | 915 |
| Rule-4.1 | 1 496 | 2 193 | 1 453 | 846 | 825 |
| Rule-4.2 | 1 497 | 2 193 | 1 453 | 854 | 835 |
| Rule-4.3 | 1 053 | 1 472 | 1 012 | 879 | 856 |
| Rule-4.4 | 1 049 | 1 467 | 1 011 | 884 | 861 |

**Table 21: Estimated proportion of years for the Sub-Antarctic that the catch limit (t) changed by at least 250 t (performance indicator C03) 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 | 0.14 | 0.15 | 0.14 | 0.01 | 0.01 |
| Rule-1.2 | 0.14 | 0.15 | 0.14 | 0.03 | 0.03 |
| Rule-1.3 | 0.14 | 0.15 | 0.13 | 0.01 | 0.01 |
| Rule-1.4 | 0.13 | 0.14 | 0.13 | 0.03 | 0.03 |
| Rule-2.1 | 0.15 | 0.16 | 0.15 | 0.02 | 0.01 |
| Rule-2.2 | 0.15 | 0.16 | 0.15 | 0.03 | 0.03 |
| Rule-2.3 | 0.14 | 0.15 | 0.14 | 0.02 | 0.02 |
| Rule-2.4 | 0.14 | 0.15 | 0.14 | 0.03 | 0.03 |
| Rule-3.1 | 0.15 | 0.16 | 0.15 | 0.02 | 0.02 |
| Rule-3.2 | 0.15 | 0.16 | 0.15 | 0.03 | 0.03 |
| Rule-3.3 | 0.14 | 0.15 | 0.14 | 0.02 | 0.02 |
| Rule-3.4 | 0.14 | 0.15 | 0.14 | 0.03 | 0.03 |
| Rule-4.1 | 0.15 | 0.16 | 0.15 | 0.01 | 0.01 |
| Rule-4.2 | 0.15 | 0.15 | 0.15 | 0.03 | 0.03 |
| Rule-4.3 | 0.14 | 0.15 | 0.14 | 0.02 | 0.02 |
| Rule-4.4 | 0.14 | 0.14 | 0.14 | 0.03 | 0.03 |

**Table 22: Expected (mean) values for the Chatham Rise 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 | 40.9 | 61.3 | 60.6 | 40.8 | 58.3 |
| Rule-1.2 | 41.0 | 61.5 | 60.8 | 40.9 | 58.3 |
| Rule-1.3 | 40.9 | 61.3 | 60.9 | 40.3 | 57.3 |
| Rule-1.4 | 40.9 | 61.3 | 61.0 | 40.2 | 57.1 |
| Rule-2.1 | 40.6 | 59.1 | 58.7 | 38.9 | 54.9 |
| Rule-2.2 | 40.6 | 59.1 | 58.7 | 38.8 | 54.6 |
| Rule-2.3 | 40.5 | 58.3 | 58.5 | 37.8 | 52.8 |
| Rule-2.4 | 40.5 | 58.4 | 58.5 | 37.8 | 52.3 |
| Rule-3.1 | 40.5 | 58.2 | 58.0 | 38.3 | 55.2 |
| Rule-3.2 | 40.5 | 58.2 | 58.0 | 38.3 | 54.8 |
| Rule-3.3 | 40.4 | 57.4 | 57.6 | 37.0 | 51.0 |
| Rule-3.4 | 40.4 | 57.4 | 57.6 | 36.9 | 50.2 |
| Rule-4.1 | 40.7 | 59.9 | 59.5 | 39.8 | 57.4 |
| Rule-4.2 | 40.8 | 60.0 | 59.5 | 39.7 | 57.1 |
| Rule-4.3 | 40.7 | 59.8 | 59.6 | 39.0 | 55.1 |
| Rule-4.4 | 40.7 | 59.7 | 59.7 | 38.9 | 54.6 |

**Table 23: Estimated values for the Chatham Rise 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 | 1.00 | 1.00 | 1.00 | 1.00 | 0.96 |
| Rule-1.2 | 1.00 | 1.00 | 1.00 | 1.00 | 0.96 |
| Rule-1.3 | 1.00 | 1.00 | 1.00 | 1.00 | 0.96 |
| Rule-1.4 | 1.00 | 1.00 | 1.00 | 1.00 | 0.95 |
| Rule-2.1 | 1.00 | 1.00 | 1.00 | 0.99 | 0.94 |
| Rule-2.2 | 1.00 | 1.00 | 1.00 | 0.99 | 0.94 |
| Rule-2.3 | 1.00 | 1.00 | 0.99 | 1.00 | 0.93 |
| Rule-2.4 | 1.00 | 1.00 | 0.99 | 1.00 | 0.92 |
| Rule-3.1 | 1.00 | 1.00 | 1.00 | 1.00 | 0.96 |
| Rule-3.2 | 1.00 | 1.00 | 1.00 | 1.00 | 0.95 |
| Rule-3.3 | 1.00 | 1.00 | 0.99 | 0.99 | 0.91 |
| Rule-3.4 | 1.00 | 1.00 | 0.99 | 0.99 | 0.90 |
| Rule-4.1 | 1.00 | 1.00 | 1.00 | 1.00 | 0.97 |
| Rule-4.2 | 1.00 | 1.00 | 1.00 | 1.00 | 0.96 |
| Rule-4.3 | 1.00 | 1.00 | 0.99 | 1.00 | 0.94 |
| Rule-4.4 | 1.00 | 1.00 | 0.99 | 1.00 | 0.94 |

**Table 24: Estimated values for the Chatham Rise 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 | 1.00 | 1.00 | 0.99 | 0.99 | 0.94 |
| Rule-1.2 | 1.00 | 1.00 | 0.99 | 0.99 | 0.93 |
| Rule-1.3 | 0.99 | 1.00 | 0.98 | 0.99 | 0.93 |
| Rule-1.4 | 0.99 | 1.00 | 0.98 | 0.99 | 0.92 |
| Rule-2.1 | 1.00 | 1.00 | 1.00 | 0.98 | 0.91 |
| Rule-2.2 | 1.00 | 1.00 | 1.00 | 0.98 | 0.91 |
| Rule-2.3 | 0.99 | 1.00 | 0.98 | 0.98 | 0.90 |

| | | | | | |
|---|---|---|---|---|---|
| Rule-2.4 | 0.99 | 1.00 | 0.98 | 0.97 | 0.89 |
| Rule-3.1 | 1.00 | 1.00 | 1.00 | 0.98 | 0.93 |
| Rule-3.2 | 1.00 | 1.00 | 1.00 | 0.98 | 0.92 |
| Rule-3.3 | 0.99 | 1.00 | 0.97 | 0.97 | 0.88 |
| Rule-3.4 | 0.99 | 1.00 | 0.97 | 0.97 | 0.86 |
| Rule-4.1 | 1.00 | 1.00 | 1.00 | 0.99 | 0.94 |
| Rule-4.2 | 1.00 | 1.00 | 1.00 | 0.98 | 0.93 |
| Rule-4.3 | 0.99 | 1.00 | 0.98 | 0.98 | 0.91 |
| Rule-4.4 | 0.99 | 1.00 | 0.98 | 0.98 | 0.91 |

**Table 25: Estimated values for the Chatham Rise 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 | 954 | 1 420 | 1 401 | 952 | 1 354 |
| Rule-1.2 | 950 | 1 413 | 1 394 | 948 | 1 348 |
| Rule-1.3 | 952 | 1 418 | 1 369 | 968 | 1 371 |
| Rule-1.4 | 952 | 1 417 | 1 369 | 968 | 1 367 |
| Rule-2.1 | 963 | 1 491 | 1 461 | 1 000 | 1 409 |
| Rule-2.2 | 963 | 1 491 | 1 461 | 1 001 | 1 406 |
| Rule-2.3 | 964 | 1 511 | 1 433 | 1 032 | 1 429 |
| Rule-2.4 | 964 | 1 509 | 1 432 | 1 031 | 1 416 |
| Rule-3.1 | 968 | 1 518 | 1 484 | 1 023 | 1 458 |
| Rule-3.2 | 968 | 1 518 | 1 484 | 1 024 | 1 449 |
| Rule-3.3 | 966 | 1 541 | 1 452 | 1 053 | 1 438 |
| Rule-3.4 | 967 | 1 541 | 1 451 | 1 054 | 1 423 |
| Rule-4.1 | 961 | 1 464 | 1 438 | 982 | 1 405 |
| Rule-4.2 | 959 | 1 462 | 1 436 | 982 | 1 400 |
| Rule-4.3 | 959 | 1 467 | 1 401 | 1 001 | 1 400 |
| Rule-4.4 | 961 | 1 470 | 1 406 | 1 003 | 1 397 |

**Table 26: Estimated standard deviation for the Chatham Rise 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 | 355 | 420 | 623 | 256 | 472 |
| Rule-1.2 | 354 | 418 | 620 | 255 | 472 |
| Rule-1.3 | 307 | 334 | 518 | 261 | 491 |
| Rule-1.4 | 306 | 334 | 515 | 261 | 495 |
| Rule-2.1 | 438 | 470 | 701 | 280 | 531 |
| Rule-2.2 | 438 | 470 | 701 | 281 | 534 |
| Rule-2.3 | 360 | 369 | 587 | 288 | 575 |
| Rule-2.4 | 359 | 368 | 586 | 288 | 586 |
| Rule-3.1 | 474 | 492 | 734 | 278 | 519 |
| Rule-3.2 | 474 | 492 | 735 | 280 | 530 |
| Rule-3.3 | 379 | 382 | 613 | 297 | 613 |
| Rule-3.4 | 378 | 382 | 613 | 298 | 631 |
| Rule-4.1 | 413 | 444 | 669 | 265 | 483 |
| Rule-4.2 | 412 | 444 | 668 | 266 | 490 |
| Rule-4.3 | 340 | 350 | 555 | 274 | 534 |
| Rule-4.4 | 340 | 351 | 553 | 277 | 539 |

**Table 27: Estimated proportion of years for the Chatham Rise that the catch limit (t) changed by at least 250 t (performance indicator C03) 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 | 0.05 | 0.09 | 0.10 | 0.01 | 0.01 |
| Rule-1.2 | 0.05 | 0.09 | 0.10 | 0.01 | 0.01 |
| Rule-1.3 | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 |
| Rule-1.4 | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 |
| Rule-2.1 | 0.08 | 0.11 | 0.12 | 0.01 | 0.01 |
| Rule-2.2 | 0.08 | 0.11 | 0.12 | 0.01 | 0.01 |
| Rule-2.3 | 0.01 | 0.02 | 0.03 | 0.01 | 0.01 |
| Rule-2.4 | 0.01 | 0.02 | 0.03 | 0.01 | 0.01 |
| Rule-3.1 | 0.10 | 0.12 | 0.13 | 0.01 | 0.01 |
| Rule-3.2 | 0.10 | 0.12 | 0.13 | 0.01 | 0.01 |
| Rule-3.3 | 0.01 | 0.02 | 0.03 | 0.01 | 0.01 |
| Rule-3.4 | 0.01 | 0.02 | 0.03 | 0.01 | 0.01 |
| Rule-4.1 | 0.07 | 0.10 | 0.11 | 0.01 | 0.01 |
| Rule-4.2 | 0.07 | 0.10 | 0.11 | 0.01 | 0.01 |
| Rule-4.3 | 0.01 | 0.02 | 0.03 | 0.01 | 0.01 |
| Rule-4.4 | 0.01 | 0.02 | 0.03 | 0.01 | 0.01 |

## 3.4 Evaluations of the HCRs using alternative models

For the Sub-Antarctic, each HCR was run for the base case from Dunn et al. (2021b) and selected sensitivity models, and the results for the performance indicators given in Table 28. 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.

For the Chatham Rise, each HCR was run for the base case from Holmes (2021) and selected sensitivity models, and the results for the performance indicators given in Table 29. 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 468–1700 t.

**Table 28: Estimated values for the Sub-Antarctic of the performance indicators (P01–P09 and C01–C03) for each candidate HCR assuming recent YCS. The description of each performance indicator is given in Table 3 above.**

| FILE | Rule | P01 | P02 | P03 | P04 | P05 | P06 | P07 | P08 | P09 | C01 | C02 | C03 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2021 Base case | Rule-1.1 | 1.02 | 0.41 | 1.00 | 1.00 | 0.10 | 0.27 | 0.14 | 0.02 | 0.51 | 2 734 | 1 250 | 0.14 |
| | Rule-2.1 | 1.02 | 0.41 | 1.00 | 1.00 | 0.10 | 0.26 | 0.13 | 0.02 | 0.51 | 2 736 | 1 545 | 0.15 |
| | Rule-3.1 | 1.02 | 0.41 | 1.00 | 1.00 | 0.10 | 0.27 | 0.13 | 0.02 | 0.50 | 2 737 | 1 674 | 0.15 |
| | Rule-4.1 | 1.02 | 0.41 | 1.00 | 1.00 | 0.10 | 0.26 | 0.13 | 0.02 | 0.51 | 2 737 | 1 496 | 0.15 |
| 2024 Base case with low M | Rule-1.1 | 1.36 | 0.54 | 1.00 | 1.00 | 0.00 | 0.01 | 0.66 | 0.25 | 0.95 | 1 097 | 405 | 0.09 |
| | Rule-2.1 | 1.33 | 0.53 | 1.00 | 1.00 | 0.00 | 0.02 | 0.61 | 0.21 | 0.94 | 1 145 | 483 | 0.12 |
| | Rule-3.1 | 1.31 | 0.53 | 1.00 | 1.00 | 0.00 | 0.02 | 0.59 | 0.20 | 0.93 | 1 162 | 515 | 0.13 |
| | Rule-4.1 | 1.33 | 0.53 | 1.00 | 1.00 | 0.00 | 0.02 | 0.62 | 0.22 | 0.94 | 1 135 | 458 | 0.11 |
| 2024 Base case with high M | Rule-1.1 | 1.48 | 0.59 | 1.00 | 1.00 | 0.00 | 0.01 | 0.79 | 0.44 | 0.97 | 2 290 | 996 | 0.19 |
| | Rule-2.1 | 1.46 | 0.58 | 1.00 | 1.00 | 0.00 | 0.01 | 0.76 | 0.40 | 0.96 | 2 426 | 1 144 | 0.21 |
| | Rule-3.1 | 1.45 | 0.58 | 1.00 | 1.00 | 0.00 | 0.01 | 0.75 | 0.39 | 0.96 | 2 475 | 1 205 | 0.22 |
| | Rule-4.1 | 1.46 | 0.58 | 1.00 | 1.00 | 0.00 | 0.01 | 0.77 | 0.41 | 0.97 | 2 394 | 1 096 | 0.21 |
| 2024 Base case with h = 0.5 | Rule-1.1 | 1.25 | 0.50 | 1.00 | 1.00 | 0.03 | 0.10 | 0.47 | 0.20 | 0.79 | 1 733 | 873 | 0.15 |
| | Rule-2.1 | 1.23 | 0.49 | 1.00 | 1.00 | 0.03 | 0.10 | 0.44 | 0.17 | 0.78 | 1 788 | 1 011 | 0.18 |
| | Rule-3.1 | 1.22 | 0.49 | 1.00 | 1.00 | 0.03 | 0.10 | 0.42 | 0.16 | 0.77 | 1 808 | 1 068 | 0.19 |
| | Rule-4.1 | 1.24 | 0.49 | 1.00 | 1.00 | 0.03 | 0.10 | 0.44 | 0.18 | 0.78 | 1 777 | 973 | 0.18 |
| 2024 Base case with h = 0.66 | Rule-1.1 | 1.34 | 0.54 | 1.00 | 1.00 | 0.00 | 0.03 | 0.61 | 0.25 | 0.91 | 1 708 | 786 | 0.15 |
| | Rule-2.1 | 1.32 | 0.53 | 1.00 | 1.00 | 0.00 | 0.03 | 0.57 | 0.22 | 0.90 | 1 784 | 911 | 0.18 |
| | Rule-3.1 | 1.31 | 0.52 | 1.00 | 1.00 | 0.00 | 0.03 | 0.56 | 0.21 | 0.89 | 1 811 | 963 | 0.19 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rule-4.1 | 1.32 | 0.53 | 1.00 | 1.00 | 0.00 | 0.03 | 0.58 | 0.23 | 0.90 | 1 768 | 874 | 0.17 |
| 2024 Base case with h = 1.00 | Rule-1.1 | 1.42 | 0.57 | 1.00 | 1.00 | 0.00 | 0.01 | 0.75 | 0.36 | 0.97 | 1 776 | 781 | 0.16 |
| | Rule-2.1 | 1.40 | 0.56 | 1.00 | 1.00 | 0.00 | 0.01 | 0.72 | 0.32 | 0.96 | 1 877 | 902 | 0.18 |
| | Rule-3.1 | 1.39 | 0.56 | 1.00 | 1.00 | 0.00 | 0.01 | 0.70 | 0.31 | 0.96 | 1 914 | 952 | 0.19 |
| | Rule-4.1 | 1.40 | 0.56 | 1.00 | 1.00 | 0.00 | 0.01 | 0.72 | 0.33 | 0.96 | 1 854 | 863 | 0.18 |

**Table 29: Estimated values for the Chatham Rise of the performance indicators (P01–P09 and C01–C03) for each candidate HCR assuming recent YCS. The description of each performance indicator is given in Table 3 above.**

| FILE | Rule | P01 | P02 | P03 | P04 | P05 | P06 | P07 | P08 | P09 | C01 | C02 | C03 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2021 Base case | Rule-1.1 | 1.02 | 0.41 | 1.00 | 1.00 | 0.12 | 0.28 | 0.16 | 0.04 | 0.50 | 954 | 355 | 0.05 |
| | Rule-2.1 | 1.02 | 0.41 | 1.00 | 1.00 | 0.10 | 0.28 | 0.15 | 0.03 | 0.49 | 963 | 438 | 0.08 |
| | Rule-3.1 | 1.01 | 0.40 | 1.00 | 1.00 | 0.10 | 0.28 | 0.14 | 0.03 | 0.49 | 968 | 474 | 0.10 |
| | Rule-4.1 | 1.02 | 0.41 | 1.00 | 1.00 | 0.11 | 0.28 | 0.15 | 0.03 | 0.49 | 961 | 413 | 0.07 |
| 2024 Base case with low M | Rule-1.1 | 0.89 | 0.36 | 1.00 | 0.99 | 0.28 | 0.52 | 0.06 | 0.01 | 0.27 | 887 | 319 | 0.04 |
| | Rule-2.1 | 0.90 | 0.36 | 1.00 | 0.99 | 0.22 | 0.48 | 0.05 | 0.01 | 0.28 | 876 | 415 | 0.08 |
| | Rule-3.1 | 0.91 | 0.36 | 1.00 | 1.00 | 0.22 | 0.47 | 0.05 | 0.01 | 0.28 | 873 | 457 | 0.10 |
| | Rule-4.1 | 0.90 | 0.36 | 1.00 | 0.99 | 0.23 | 0.49 | 0.05 | 0.01 | 0.27 | 878 | 397 | 0.08 |
| 2024 Base case with high M | Rule-1.1 | 1.14 | 0.46 | 1.00 | 1.00 | 0.06 | 0.17 | 0.32 | 0.10 | 0.67 | 1 237 | 484 | 0.08 |
| | Rule-2.1 | 1.13 | 0.45 | 1.00 | 1.00 | 0.05 | 0.17 | 0.29 | 0.08 | 0.66 | 1 271 | 576 | 0.11 |
| | Rule-3.1 | 1.12 | 0.45 | 1.00 | 1.00 | 0.06 | 0.17 | 0.28 | 0.08 | 0.65 | 1 285 | 616 | 0.13 |
| | Rule-4.1 | 1.13 | 0.45 | 1.00 | 1.00 | 0.05 | 0.17 | 0.30 | 0.09 | 0.66 | 1 260 | 542 | 0.10 |
| 2024 Base case with h = 0.5 | Rule-1.1 | 0.81 | 0.33 | 0.99 | 0.87 | 0.45 | 0.63 | 0.08 | 0.02 | 0.23 | 807 | 370 | 0.03 |
| | Rule-2.1 | 0.86 | 0.34 | 1.00 | 0.96 | 0.37 | 0.58 | 0.07 | 0.02 | 0.25 | 803 | 450 | 0.07 |
| | Rule-3.1 | 0.87 | 0.35 | 1.00 | 0.97 | 0.34 | 0.57 | 0.07 | 0.02 | 0.25 | 801 | 487 | 0.09 |
| | Rule-4.1 | 0.86 | 0.34 | 1.00 | 0.96 | 0.38 | 0.59 | 0.07 | 0.02 | 0.24 | 803 | 439 | 0.07 |
| 2024 Base case with h = 0.66 | Rule-1.1 | 0.94 | 0.38 | 1.00 | 0.98 | 0.23 | 0.43 | 0.11 | 0.03 | 0.37 | 884 | 335 | 0.04 |
| | Rule-2.1 | 0.95 | 0.38 | 1.00 | 0.99 | 0.18 | 0.40 | 0.10 | 0.02 | 0.37 | 881 | 421 | 0.08 |
| | Rule-3.1 | 0.95 | 0.38 | 1.00 | 0.99 | 0.17 | 0.40 | 0.10 | 0.02 | 0.37 | 882 | 458 | 0.09 |
| | Rule-4.1 | 0.95 | 0.38 | 1.00 | 0.99 | 0.19 | 0.41 | 0.10 | 0.03 | 0.37 | 881 | 401 | 0.07 |
| 2024 Base case with h = 1.00 | Rule-1.1 | 1.06 | 0.42 | 1.00 | 1.00 | 0.07 | 0.22 | 0.19 | 0.05 | 0.57 | 995 | 351 | 0.05 |
| | Rule-2.1 | 1.05 | 0.42 | 1.00 | 1.00 | 0.07 | 0.22 | 0.17 | 0.04 | 0.55 | 1 011 | 436 | 0.09 |
| | Rule-3.1 | 1.04 | 0.42 | 1.00 | 1.00 | 0.07 | 0.22 | 0.17 | 0.03 | 0.55 | 1 018 | 473 | 0.10 |
| | Rule-4.1 | 1.05 | 0.42 | 1.00 | 1.00 | 0.07 | 0.22 | 0.18 | 0.04 | 0.56 | 1 007 | 408 | 0.08 |

## 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 the same as that estimated for the most recent 10 years, that surveys are conducted at 2-yearly intervals in each area with associated age composition data, and annual fishery age composition data are available to update the assessments.

The HCRs and MPs were based on the structure of the recent Sub-Antarctic (Dunn et al. 2021b) and Chatham Rise (Holmes 2021) stock assessments. 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 hake in the Sub-Antarctic 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 Dunn et al. (2021b), the current stock status is estimated to be above the target, assuming recent year classes were at the level of the most recent ten years estimated in the base case model. Based on the projections in Dunn et al. (2021b), the stock status would be unlikely to change over the next five years at the level of the current catch.

The MP evaluation for the Sub-Antarctic suggested a target biomass range (35–50% $B_0$) would be appropriate for maintaining the stock well above the sustainability threshold of 20% $B_0$) and at a level that would fluctuate about the target of 40% $B_0$. The annual catches evaluated by the HCRs yielded average annual catches of about 2700 t and a catch limit of between 3800–4400 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 30.

Reference points for hake in the Chatham Rise 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 Holmes (2021), the current stock status is estimated to be above the target, assuming recent year classes were at the level of the most recent ten years estimated in the base case model. Based on the projections in Holmes (2021), the stock status would be unlikely to change over the next five years at the level of the current catch.

The MP evaluation for the Chatham Rise suggested a target biomass range (35–50% $B_0$) would be appropriate for maintaining the stock well above the sustainability threshold of 20% $B_0$) and at a level that would fluctuate about the target of 40% $B_0$. The annual catches evaluated by the HCRs yielded average annual catches of about 950 t and a catch limit of between 1300–1400 t for 2025 with the current level of recruitments, 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 31.

**Table 30: Sub-Antarctic 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.**

| | | Rule-1.1 | | Rule-2.1 | | Rule-3.1 | | Rule-4.1 |
|---|---|---|---|---|---|---|---|---|
| SSB (%$B_0$) | *U* | Catch limit | *U* | Catch limit | *U* | Catch limit | *U* | Catch limit |
| 5 | 0.11 | 319 | 0.01 | 44 | 0.00 | 0 | 0.00 | 0 |
| 10 | 0.11 | 638 | 0.03 | 177 | 0.00 | 0 | 0.00 | 0 |
| 15 | 0.11 | 956 | 0.04 | 398 | 0.02 | 184 | 0.03 | 230 |
| 20 | 0.11 | 1 275 | 0.06 | 707 | 0.04 | 489 | 0.05 | 613 |
| 25 | 0.11 | 1 594 | 0.07 | 1 105 | 0.06 | 918 | 0.08 | 1 149 |
| 30 | 0.11 | 1 913 | 0.09 | 1 592 | 0.08 | 1 468 | 0.10 | 1 838 |
| 35 | 0.11 | 2 232 | 0.10 | 2 166 | 0.10 | 2 141 | 0.12 | 2 401 |
| 40 | 0.11 | 2 551 | 0.12 | 2 829 | 0.12 | 2 936 | 0.12 | 2 744 |
| 45 | 0.11 | 2 869 | 0.12 | 3 183 | 0.12 | 3 303 | 0.12 | 3 087 |
| 50 | 0.11 | 3 188 | 0.12 | 3 537 | 0.12 | 3 670 | 0.12 | 3 431 |
| 55 | 0.11 | 3 507 | 0.12 | 3 891 | 0.12 | 4 037 | 0.12 | 3 774 |
| 60 | 0.11 | 3 826 | 0.12 | 4 244 | 0.12 | 4 405 | 0.12 | 4 117 |
| 65 | 0.11 | 4 145 | 0.12 | 4 598 | 0.12 | 4 772 | 0.12 | 4 460 |
| 70 | 0.11 | 4 463 | 0.12 | 4 952 | 0.12 | 5 139 | 0.12 | 4 803 |
| 75 | 0.11 | 4 782 | 0.12 | 5 305 | 0.12 | 5 506 | 0.12 | 5 146 |
| 80 | 0.11 | 5 101 | 0.12 | 5 659 | 0.12 | 5 873 | 0.12 | 5 489 |
| 85 | 0.11 | 5 420 | 0.12 | 6 013 | 0.12 | 6 240 | 0.12 | 5 832 |
| 90 | 0.11 | 5 739 | 0.12 | 6 366 | 0.12 | 6 607 | 0.12 | 6 175 |
| 95 | 0.11 | 6 058 | 0.12 | 6 720 | 0.12 | 6 974 | 0.12 | 6 518 |

**Table 31: Chatham Rise 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.**

| | | Rule-1.1 | | Rule-2.1 | | Rule-3.1 | | Rule-4.1 |
|---|---|---|---|---|---|---|---|---|
| SSB (%$B_0$) | *U* | Catch limit | *U* | Catch limit | *U* | Catch limit | *U* | Catch limit |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 5 | 0.07 | 118 | 0.01 | 16 | 0.00 | 0 | 0.00 | 0 |
| 10 | 0.07 | 237 | 0.02 | 65 | 0.00 | 0 | 0.00 | 0 |
| 15 | 0.07 | 355 | 0.03 | 147 | 0.01 | 68 | 0.02 | 84 |
| 20 | 0.07 | 474 | 0.04 | 261 | 0.03 | 181 | 0.03 | 224 |
| 25 | 0.07 | 592 | 0.05 | 408 | 0.04 | 339 | 0.05 | 420 |
| 30 | 0.07 | 711 | 0.06 | 588 | 0.06 | 542 | 0.07 | 672 |
| 35 | 0.07 | 829 | 0.07 | 800 | 0.07 | 791 | 0.08 | 878 |
| 40 | 0.07 | 948 | 0.08 | 1 045 | 0.08 | 1 085 | 0.08 | 1 003 |
| 45 | 0.07 | 1 066 | 0.08 | 1 175 | 0.08 | 1 220 | 0.08 | 1 129 |
| 50 | 0.07 | 1 184 | 0.08 | 1 306 | 0.08 | 1 356 | 0.08 | 1 254 |
| 55 | 0.07 | 1 303 | 0.08 | 1 437 | 0.08 | 1 491 | 0.08 | 1 379 |
| 60 | 0.07 | 1 421 | 0.08 | 1 567 | 0.08 | 1 627 | 0.08 | 1 505 |
| 65 | 0.07 | 1 540 | 0.08 | 1 698 | 0.08 | 1 762 | 0.08 | 1 630 |
| 70 | 0.07 | 1 658 | 0.08 | 1 828 | 0.08 | 1 898 | 0.08 | 1 756 |
| 75 | 0.07 | 1 777 | 0.08 | 1 959 | 0.08 | 2 034 | 0.08 | 1 881 |
| 80 | 0.07 | 1 895 | 0.08 | 2 090 | 0.08 | 2 169 | 0.08 | 2 006 |
| 85 | 0.07 | 2 013 | 0.08 | 2 220 | 0.08 | 2 305 | 0.08 | 2 132 |
| 90 | 0.07 | 2 132 | 0.08 | 2 351 | 0.08 | 2 440 | 0.08 | 2 257 |
| 95 | 0.07 | 2 250 | 0.08 | 2 481 | 0.08 | 2 576 | 0.08 | 2 383 |

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