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A stock assessment of red gurnard in GUR 7 for 2022

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EXECUTIVE SUMMARY

Langley, A.D.[1] (2022). A stock assessment of red gurnard in GUR 7 for 2022.

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The red gurnard (GUR, *Chelidonichthys kumu*) fishery in GUR 7 is dominated by the inshore bottom trawlers operating off the west coast of the South Island (WCSI) and in Tasman Bay/Golden Bay (TBGB). Red gurnard is predominantly caught in conjunction with trawls targeting flatfish species, red cod, and barracouta in relatively shallow waters (10–60 m depth). Since 2010, there has been an increase in the targeting of red gurnard, particularly in TBGB.

Red gurnard is monitored by the biennial west coast South Island (WCSI) *Kaharoa* inshore trawl survey. The red gurnard biomass indices from the four most recent inshore trawl surveys (2015, 2017, 2019, and 2021) were 3–4 fold larger than the biomass indices from 1992 to 2009 and the 2021 index was the highest of the series. Red gurnard abundance increased in both the WCSI and TBGB portions of the trawl survey area.

A statistical age-structured population model was configured for GUR 7 using the Stock Synthesis software. The model incorporated data to the 2020/21 fishing year (2021 model year). The input data were limited to commercial catches from 1987 to 2021 and the time series of *Kaharoa* WCSI trawl survey biomass indices and associated length and age compositions.

The assessment model estimated that stock abundance increased considerably from 2010 following higher levels of recruitment during 2008–2019. For all model options, current (2021) stock status was estimated to be at about the equilibrium, unexploited biomass level (i.e., SB_0). Current rates of fishing mortality were estimated to be well below the fishing mortality threshold ($F_{SB40\%}$). Potential current yields (at $F_{SB40\%}$) were estimated to be about 2000–3000 t, and therefore considerably higher than recent catches and the 2021/22 TACC (1298 t).

Stock projections were conducted for a 5-year period (i.e., 2022–2026) assuming recent (2011–2020) levels of recruitment. Commercial catches in the projection period were held constant at the 2021/22 TACC. Stock abundance was predicted to remain at about the current (2021) level during the projection period (at about SB_0).

A range of potential management procedures (MPs) were evaluated that directly link changes in the GUR 7 TACC to the red gurnard biomass indices from the biennial *Kaharoa* WCSI inshore trawl surveys. Simulation modelling indicated that a simple MP would improve utilisation while maintaining the stock at sustainable (target) levels. Further consultation is required between Fisheries New Zealand and key stakeholders to determine the most appropriate MP and formulate an associated management plan to mitigate factors that may compromise the performance of the MP (‘break out’ rules).

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1. INTRODUCTION

The red gurnard (GUR, *Chelidonichthys kumu*) fishery in GUR 7 is dominated by the inshore bottom trawlers operating off the west coast of the South Island (WCSI) and Tasman Bay/Golden Bay (TBGB) (Figure 1). Red gurnard is predominantly caught in conjunction with trawls targeting flatfish species, red cod (*Pseudophycis bachus*), and barracouta (*Thyrsites atun*) in relatively shallow waters (10–60 m depth) (Starr & Kendrick 2017). Since 2010, there has been an increase in the targeting of red gurnard, particularly in TBGB (Langley 2021).

Reported commercial catches of red gurnard averaged about 400 t per annum from the 1950s until the introduction of the Quota Management System in 1986 (Fisheries New Zealand 2021). The initial Total Allowable Catch (TAC) was set at 610 t in 1986/87, but was increased to 678 t following Quota Appeal decisions. In 1991/92, the Total Allowable Commercial Catch (TACC) was increased to 815 t for a five-year period under the Adaptive Management Programme (AMP), although annual catches were well below the TACC during 1993/94–1996/97. The TACC reverted to the pre AMP level of 678 t in 1997/98.

Annual catches increased steadily from 2010/11 and the TACC was incrementally increased from 715 t to 1298 t between 2011/12 and 2020/21. Annual catches approximated the TACC during this period. Recreational catches of red gurnard are estimated to be relatively small (38 t from the 2017/18 National Panel Survey) (Fisheries New Zealand 2021).

Since 1992, R.V. *Kaharoa* has conducted fifteen trawl surveys off the west coast of the South Island and in Tasman Bay/Golden Bay (this series is referred to as the WCSI trawl survey). The trawl surveys are conducted in late summer (March–April) and have occurred biennially since 2003 (MacGibbon et al. 2022). The trawl surveys are considered to provide reliable indices of abundance for red gurnard due to the demersal habitat of the species and relatively broad distribution. The trawl surveys also provide length composition data for red gurnard and age compositions are available for a limited number of the earlier surveys (Sutton 1997, Lyon & Horn 2011).

Red gurnard CPUE indices have been derived from the WCSI flatfish and mixed trawl fisheries (Starr & Kendrick 2017). Trends in the CPUE indices deviated from the WCSI trawl survey abundance indices, particularly during the 2000s. Consequently, the CPUE indices are not considered to represent a reliable long term index of abundance for GUR 7 (Fisheries New Zealand 2021).

From 2013, the trawl survey biomass indices were applied to derive a B_{MSY}-compatible proxy for GUR 7, based on the average of the indices from 1992 to 2013 (excluding 2003) (Fisheries New Zealand 2021). Recent (2015–2021) trawl survey biomass indices have been well above the target level and have supported increases in the GUR 7 TACC. However, there has been no formal mechanism to directly link changes in TACC to the trawl survey biomass indices. To improve the utility of the WCSI trawl survey, the Southern Inshore Finfish Management Company funded an initial project to develop potential Management Procedures (MPs) for GUR 7 and other species monitored by the survey (specifically John dory JDO 7 and red cod RCO 7). The project was further progressed by Fisheries New Zealand contracted under research services project INS2021-01.

The evaluation of potential MPs for red gurnard required the development of an operating model that represented the dynamics of the GUR 7 stock. The operating model was formulated as an age-structured population model, integrating key biological parameters, commercial catches, and the timeseries of WCSI trawl survey data. The Inshore Working Group considered that the resulting population model was sufficiently robust to be adopted as a fully quantitative stock assessment for GUR 7. This report documents the results of the stock assessment and applies the assessment model to evaluate potential MPs for GUR 7. The development of a similar approach for JDO 7 and RCO 7 was not completed due to a lack of stock-specific biological information (JDO 7) and limitations in the application of the MP approach for short-lived species (RCO 7).

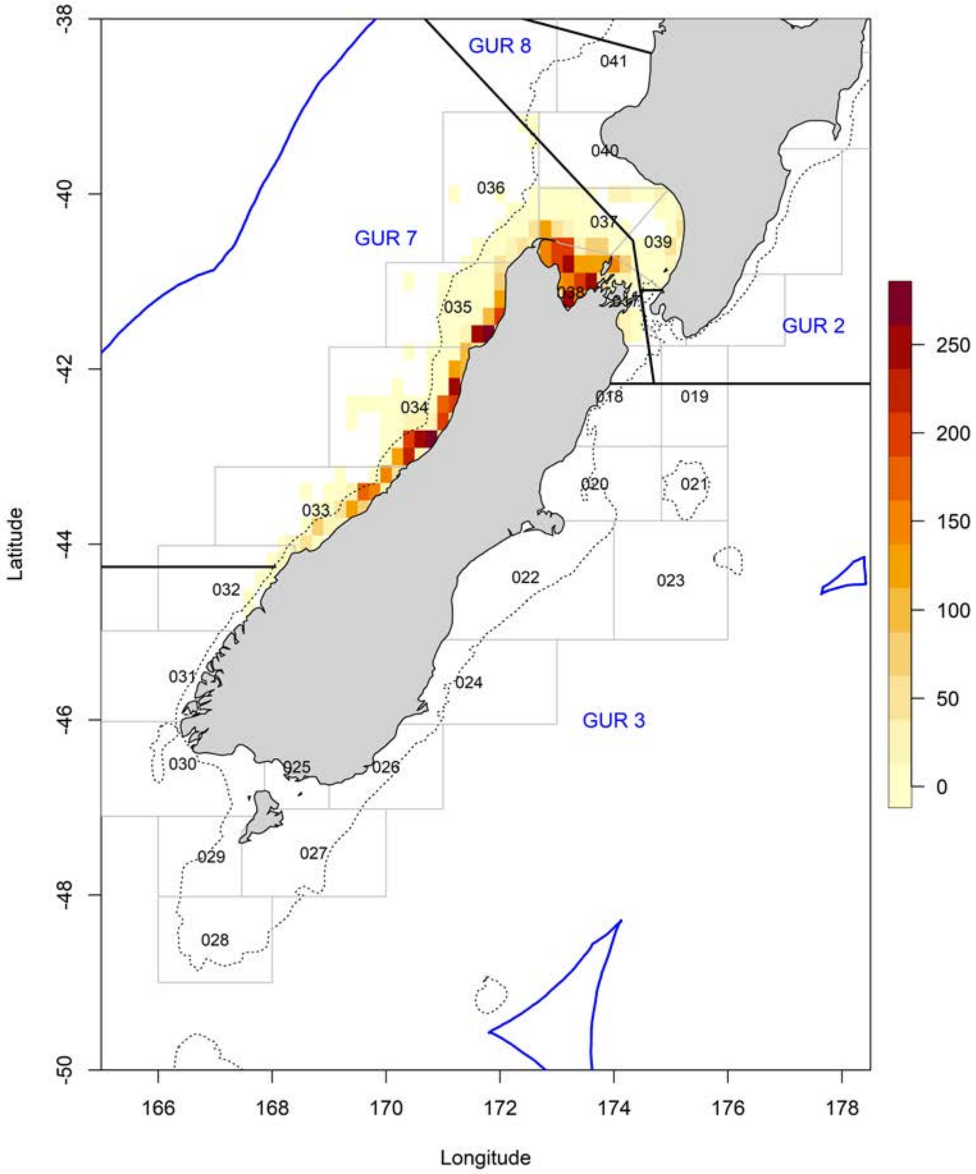

Figure 1: Spatial distribution of GUR 7 trawl red gurnard catches (t) from 2007/08 to 2020/21 fishing years (combined). The main coastal statistical areas are shown. The dotted line represents the 200 m depth contour.

2. WCSI TRAWL SURVEY

The West Coast South Island inshore trawl survey series, including the Tasman Bay/Golden Bay (TBGB) area, commenced in 1992 and has been conducted biennially since 2003 (Stevenson & Hanchet 2000, MacGibbon et al. 2022). Red gurnard is one of the target species for the trawl survey. It is one of the main species caught and there is comprehensive sampling of the red gurnard catch (including the collection of lengths and otoliths).

Red gurnard biomass indices are relatively constant for the nine surveys conducted during 1992–2009, with the exception of the lower biomass index from the 2003 survey (Table 1 and Figure 2). For the 2003 trawl survey, the abundance was low for a wide range of species from the WCSI area and the individual survey was assessed to have “extremely” low overall catchability based on the ranking approach of Francis et al. (2001) (Stevenson 2012). The approach also assigned a low catchability to the 2021 trawl survey, although there is some indication that the lower species rankings were attributable to a recent decline in the abundance for a range of the species (MacGibbon et al. 2022).

The red gurnard biomass indices from the four most recent trawl surveys (2015, 2017, 2019, and 2021) are 3–4 fold larger than the biomass indices from 1992 to 2009 and the 2021 index was the highest of the time series (Figure 2). Red gurnard abundance increased in both the WCSI and TBGB portions of the trawl survey area (MacGibbon et al. 2022).

Age compositions are available from five surveys (1994, 1995, 2003, 2005, and 2007) (Sutton 1997, Lyon & Horn 2011) and length compositions were derived for the remainder of the surveys. The age compositions were dominated by 1–6 year old fish with few fish older than 8 years.

The length compositions of red gurnard from TBGB are dominated by 20–30 cm (T.L.) fish, while larger (30–40 cm T.L.) fish predominate in the WCSI area of the trawl survey (MacGibbon et al. 2022). However, there was a general increase in the proportion of larger female fish sampled from TBGB during the four most recent surveys (2015, 2017, 2019, and 2021). The predominance of smaller/younger fish in TBGB indicates that the area represents an important nursery ground for GUR 7 (Lyon & Horn 2011, Morrison et al. 2014).

A summary of red gurnard length frequency data from the time series of trawl surveys revealed a general increase in the length of male and female fish with increasing trawl depth to about 40 m (Figure 3). Female red gurnard dominated fish sampled from shallower trawls, and male fish increasingly dominated the sampled catches from deeper trawls (Figure 3). The general trends in fish length and sex ratio were similar between the two main areas of the trawl survey (WCSI and TBGB).

Table 1: Summary of the red gurnard data from the time series of *Kaharoa* west coast South Island trawl surveys.

Year (Calendar/Model)	Biomass Index (t)	CV (%)	Age comp	Length comp	Reference
1992/1992	572	15	No	Yes	Drummond & Stevenson (1995a)
1994/1994	559	15	Yes	Yes	Drummond & Stevenson (1995b), Sutton (1997)
1995/1995	584	19	Yes	Yes	Drummond & Stevenson (1996), Sutton (1997)
1997/1997	471	13	No	Yes	Stevenson (1998), Sutton (1997)
2000/2000	625	15	No	Yes	Stevenson (2002)
2003/2003	270	20	Yes	Yes	Stevenson (2004), Lyon & Horn (2011)
2005/2005	442	17	Yes	Yes	Stevenson (2006), Lyon & Horn (2011)
2007/2007	553	17	Yes	Yes	Stevenson (2007), Lyon & Horn (2011)
2009/2009	651	18	No	Yes	Stevenson & Hanchet (2010)
2011/2011	1 070	17	No	Yes	Stevenson (2012)
2013/2013	754	12	No	Yes	MacGibbon & Stevenson (2013)
2015/2015	1 774	16	No	Yes	Stevenson & MacGibbon (2015)
2017/2017	1 708	12	No	Yes	Stevenson & MacGibbon (2018)
2019/2019	1 642	16	No	Yes	MacGibbon (2019)
2021/2021	2 019	18	No	Yes	MacGibbon et al. (2022)

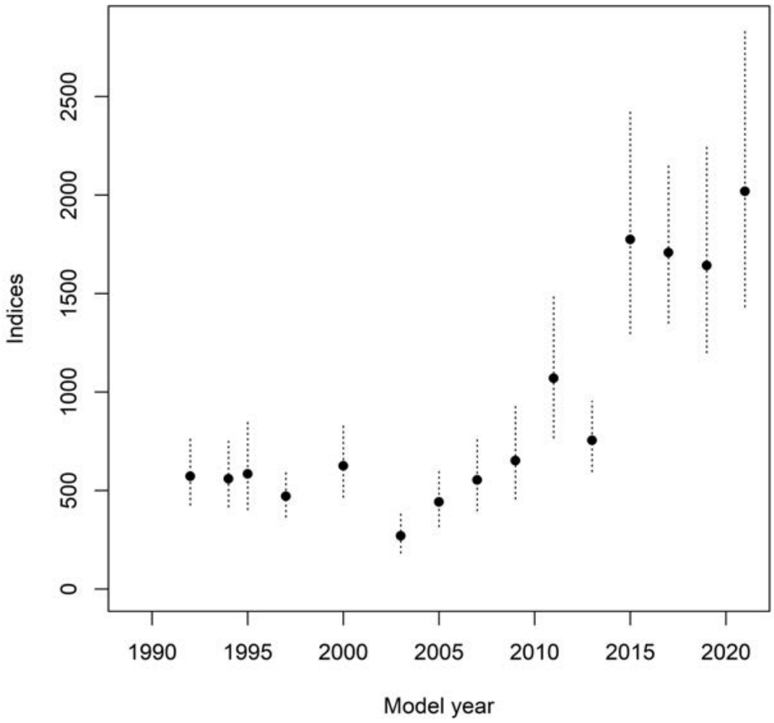

Figure 2: Red gurnard trawl survey biomass indices from the WCSI *Kaharoa* trawl surveys. The bars represent the 95% confidence intervals.

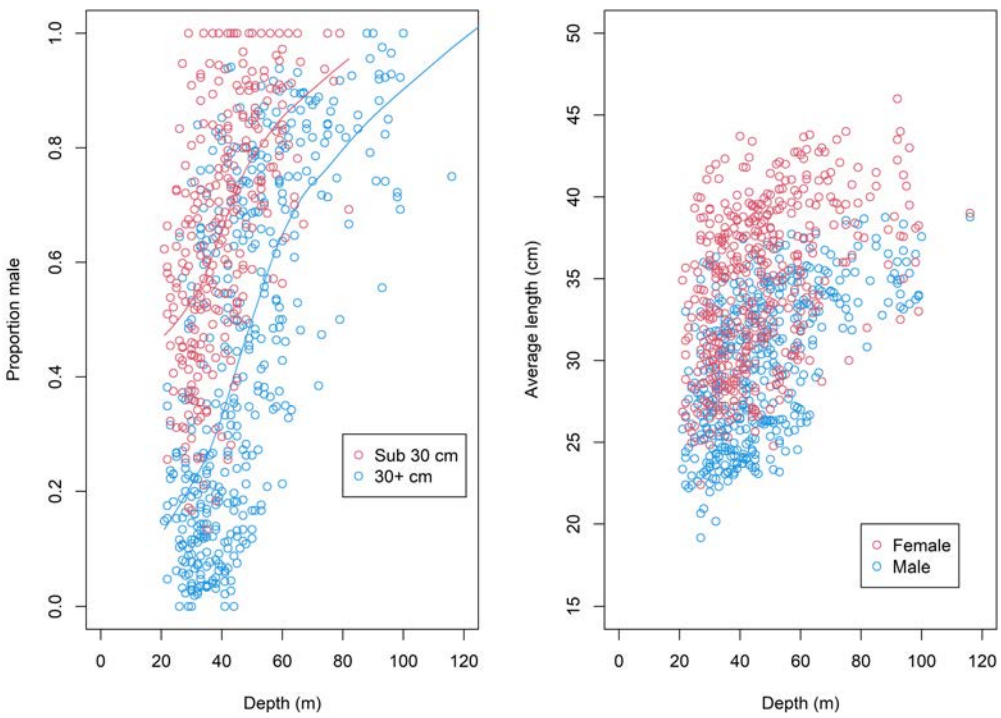

Figure 3: Proportion of male red gurnard from individual trawl survey stations by trawl depth for fish less than 30 cm (T.L.) and 30 cm and larger (left panel) and average length of male and female fish by station depth (right panel).

3. STOCK ASSESSMENT

A statistical age-structured population model was configured for GUR 7 using the Stock Synthesis (SS) software (version 3.30.17), a flexible framework for implementing statistical, age-structured population models (Methot & Wetzel 2013, Methot et al. 2020). The model incorporated data to the 2020/21 fishing year (2021 model year). The input data were limited to commercial catches from 1987–2021 and *Kaharoa* WCSI trawl survey biomass indices and associated length/age compositions (1992–2021, N = 15).

Previously, CPUE indies were derived for the GUR 7 trawl fisheries. However, the trends in the CPUE indices deviated from the trends in the abundance indices from the WCSI trawl survey. The CPUE indices are considered a less reliable indicator of stock abundance and were not included in the stock assessment.

Commercial catch data are available for the GUR 7 fishery from 1931. However, the catch data are considered less reliable for the period prior to the introduction of the Quota Management System in 1986. Annual commercial catches fluctuated during the 1990s and 2000s and then increased during 2010–2021 (Figure 4). No allowance was made for the under-reporting of catches from the commercial fishery when constructing the catch history for the model.

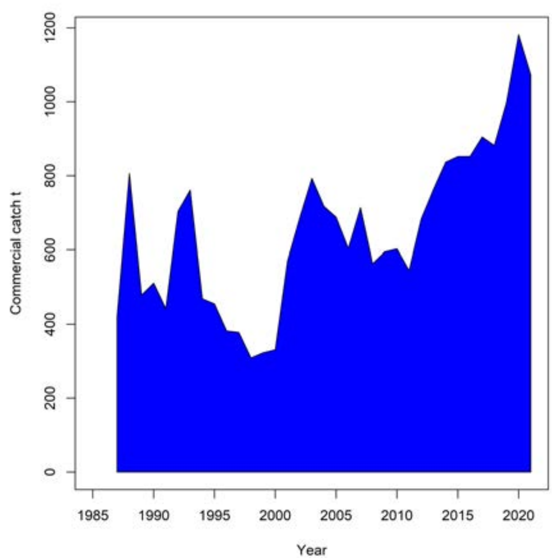

Figure 4: Annual commercial catches included in the assessment model, from 1987–2021.

No length or age composition data are available from the commercial fishery. The length composition of the red gurnard landed catch is determined, in part, by the cod end mesh size of the trawl fishery and a preferred minimum commercial fish size of about 30 cm (T.L.). The minimum cod end mesh size in the WCSI inshore trawl fishery is 100 mm, which is estimated to have a 50% selection at a length of 25.7 cm for red gurnard (Massey 1988). Nonetheless, most of the landed catch is composed of fish larger than 30 cm in length (WCSI commercial sector, pers. comm.).

Estimates of annual recreational catches of red gurnard from GUR 7 are relatively small (11–38 t) and were not included in the assessment model (Fisheries New Zealand 2021).

There are no estimates of customary catch available for GUR 7. Recent customary catches are likely to have been a minor component of the total catch and are not explicitly included in the model catch history.

3.1 Assessment model configuration

The assessment model included the period 1987 to 2021 (2020/21 fishing year). The population was partitioned by sex and included 10 age classes, the oldest age class representing an aggregated 'plus' group (10 years and older). The model was initialised in 1987 with the population age structure in an equilibrium, exploited state.

The model was structured with an annual time step and no seasonal structure. Spawning was assumed to occur instantaneously at the start of the model year and recruitment was a function of the spawning biomass at the start of the year.

The model was configured to a single fishery. The GUR 7 trawl fishery operates throughout the fishing year and catches were assigned to be taken instantaneously at the middle of the model year. The initial (1987) fishing mortality rate for the fishery was an estimated parameter, informed by a prior that inferred a relatively high level of initial fishing mortality.

The key biological parameters for the model are presented in Table 2. Natural mortality (*M*) was estimated from the 1994 and 1995 *Kaharoa* WCSI trawl survey age compositions (Sutton 1997) and the study concluded that 0.25–0.35 represented a plausible range for *M* for both male and female red gurnard. Von Bertalanffy growth parameters were also available from the same study (Figure 5).

Red gurnard reach sexual maturity at an age of 2–3 years (Fisheries New Zealand 2021); 50% of fish were assumed to be mature at age 2 years (approximately 30 cm, Figure 5) and at full maturity at age 3 years (approximately 36 cm). The assumed maturity ogive was consistent with the length and ovarian maturity stage data summarised from the time series of west coast South Island *Kaharoa* trawl surveys. Female fish were assumed to account for 50% of the population (numbers and biomass, 50:50 sex ratio).

A Beverton-Holt spawning stock-recruitment relationship (SRR) was assumed with a beta prior on the steepness parameter (*h*) (mode of prior 0.85). Recruitment deviates (1987–2020) from the SRR relationship were estimated assuming a standard deviation of the natural logarithm of recruitment (σ_R) of 0.6. Recruitment for 2021 was assumed based on the average level of recruitment from the stock-recruitment relationship.

Age composition data were available from five *Kaharoa* trawl surveys and length compositions were available from the remainder of the surveys (Table 3). For the age compositions, there was assumed to be no error associated with the age determination. The survey selectivity was parametrised using an age-based logistic function; the depth range of the survey encompasses the distribution of the older, larger fish in the population (Table 4). The selectivity of younger fish was allowed to vary for females to accommodate the differences in depth stratification of male and female fish. The availability of female red gurnard to the survey may be lower than that of males because the survey depth range is limited to depths greater than 20 m. The trawl survey catchability coefficient (*q*) was parametrised with an uninformative prior.

The selectivity of the commercial fishery was parametrised as an age-based logistic function with the two parameters informed by priors that approximate full selectivity of fish at a length of about 30 cm (T.L.), the minimum size of red gurnard in the landed catch. There are no data included in the model to directly inform the estimation of the selectivity parameters. However, the inclusion of prior values for the two parameters enables a degree of uncertainty to be incorporated in the estimation procedure.

The precision of the trawl survey biomass indices was determined from the native CV of the individual surveys; no additional process error was included for the trawl survey biomass indices. The trawl survey age and length compositions were assigned a relatively high weighting (Effective Sample Size (ESS) of 50) (see Table 3). The high weighting reflected the comprehensive sampling conducted for each survey and ensured the model was informed by these data. The weightings of the age and length observations were broadly consistent with the recommended weightings following the approach of Francis (2011).

Fishing mortality was modelled using a hybrid method that calculates the harvest rate using Pope's approximation and then converts it to an approximation of the corresponding fishery specific *F* (see Methot & Wetzel 2013 for details).

Table 2: Details of parameters that were fixed in the base model.

Natural mortality	female	0.31 y^{-1}
	male	0.31 y^{-1}
Std deviation of rec devs (*sigmaR*)		0.6
Proportion mature		0 for age 1, 0.5 for age 2, 1 for ages > 2
Length-weight [mean weight (kg) = a (length (cm))^b]		$a = 5.3 \times 10^{-6}$, $b = 3.19$
Growth parameters - female		$L\infty = 45.7$, $k = 0.40$, Length1=19.4
	male	$L\infty = 40.3$, $k = 0.37$, Length1=19.4
Coefficients of variation for length-at-age		0.10

Table 3: Summary of input data sets for the Base Case assessment model. The relative weighting includes the Effective Sample Size (ESS) of age/size composition data and the coefficient of variation (CV) associated with the abundance data. Note that model year 2021, is fishing year 2020/21, and includes the trawl survey conducted in March 2021.

Data set	Model years	Nobs	Error structure	CV /ESS
Trawl survey indices	1992, 1994, 1995, 1997, 2000, 2003, 2005, 2007, 2009, 2011, 2013, 2015, 2017, 2019, 2021	15	Lognormal	0.12–0.20
Trawl survey age comp	1994, 1995, 2003, 2005, 2007	5	Multinomial	ESS 50
Trawl survey length comp	1992, 1997, 2000, 2009, 2011, 2013, 2015, 2017, 2019, 2021	10	Multinomial	ESS 50

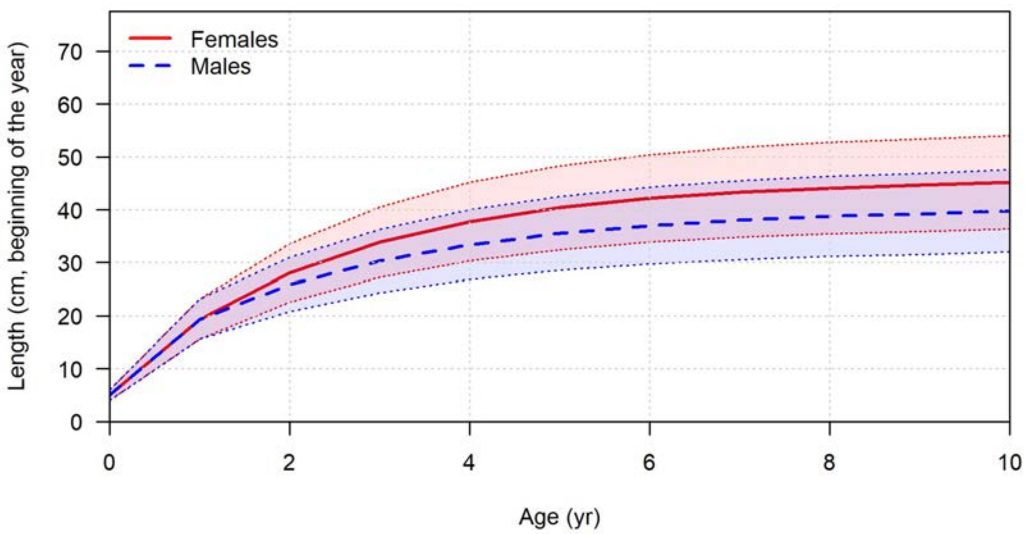

Figure 5: Growth of male and female red gurnard.

Table 4: Estimated parameters for the base model.

Parameter	Number of parameters	Parameterisation, priors, constraints
LnR_0	1	Uniform, uninformative
Stock-recruit steepness (Beverton & Holt)	1	Beta(0.80, 0.125)
Rec devs (1987–2020)	34	*SigmaR* 0.6
Selectivity trawl survey	3	Logistic, female offset
Trawl Survey ln q	1	Normal (-1.1, 1)
Selectivity BT commercial	2	Logistic
Initial F	1	Normal (0.4, 0.2)

There are five main components to the model likelihood objective function:

i. Trawl survey biomass indices. The fit to the trawl survey biomass indices assumed a lognormal error structure.
ii. Age composition data. The fit to the trawl survey age composition data assumed a multinomial error structure.
iii. Length composition data sets. The fit to the trawl survey length composition data assumed a multinomial error structure.
iv. Recruitment deviations. The likelihood is formulated to constrain recruitment deviations relative to the (assumed) standard deviation (sigmaR).
v. Parameter priors. Deviation of estimated parameter(s) from assumed prior distribution(s) (Table 4).

The formulation of the individual likelihood components is documented by Methot & Wetzel (2013). The estimation procedure minimises the negative log-likelihood of the objective function to determine the mode of the joint posterior distribution (MPD).

Model uncertainty was determined using Markov chain Monte Carlo (MCMC) methods implemented using the Metropolis-Hastings algorithm. For the selected model options, 1000 MCMC samples were drawn at 1000 intervals from a chain of 1.1 million following an initial burn-in of 100 000. The performance of the MCMC sample was evaluated using a range of diagnostics.

Stock status was determined relative to the equilibrium, unexploited spawning (mature) biomass of female fish (SB_0). Current biomass was defined as the biomass in the 2021 model year (2020/21 fishing year) ($SB_{current}$ or SB_{2021}).

Following the Fisheries New Zealand Harvest Strategy Standard (HSS), current biomass was assessed relative to the default soft limit of 20% SB_0 and hard limit of 10% SB_0 (Ministry of Fisheries 2008). The HSS includes a default target biomass level of 35% SB_0 for stocks with moderate productivity where an operational (‘real world’) SB_{MSY} has not been fully evaluated. The Inshore Working Group accepted 35% SB_0 as an appropriate SB_{MSY} proxy for GUR 7.

Fishing mortality (2021) was reported relative to the default threshold level, i.e., $F_{SB40\%}$ (Ministry of Fisheries 2008). The reference level of age-specific fishing mortality was determined from the composite age-specific fishing mortality from the last year of the model data period (2020/21). Estimates of equilibrium yield and current (2021) yield were determined from the $F_{SB40\%}$ level of fishing mortality.

3.2 Model results

3.2.1 Parameter estimation

Male fish were estimated to be fully selected by the *Kaharoa* WCSI trawl survey from 2 years old, with lower selectivity (approx. 50%) for one year old fish (Figure 6). The selectivity of female fish was estimated to be lower than males (Figure 6). This is consistent with the higher proportion of female red gurnard in shallower (20–30 m) depths, suggesting a higher proportion of female fish in areas less than 20 m in depth not included within the survey area.

The selectivity of the commercial fishery approximated the functional form assumed from the median of the prior values, with full selectivity attained from about 3 years old (Figure 6). There was uncertainty introduced in the estimation of the selectivity of 2 and 3 year old fish in the MCMC sampling procedure (Figure 7).

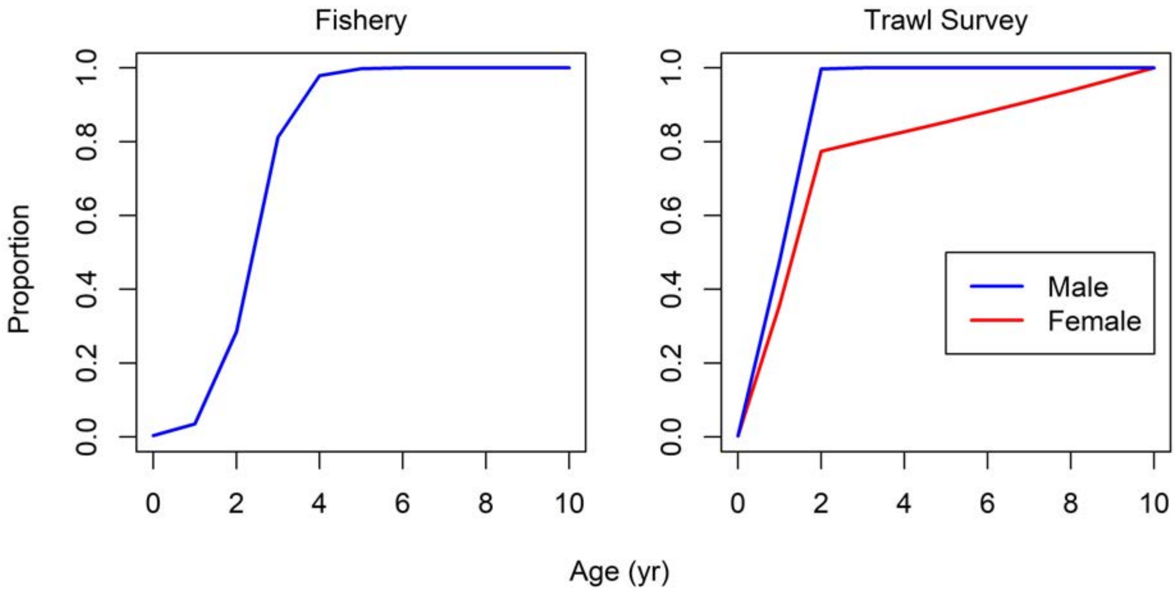

Figure 6: Age selectivity functions for the commercial fishery and the WCSI trawl survey (MPD results).

For the main productivity parameter (ln*R0*, the natural logarithm of R_0), the MPD value of 9.01 was at the lower range of the posterior distribution of the MCMC samples (Figure 7). Regardless, the overall scale of annual recruitments was very similar for the MPD and median of the MCMCs (Figure 8). The distribution of the steepness parameter approximated the prior distribution (Figure 7).

The median value of the initial fishing mortality parameter was higher than the prior distribution (Normal mean = 0.4, sd = 0.2), suggesting some information in the earlier (1994 and 1995) age composition data (Figure 7). Model trials with alternative priors (mean 0.2 or 0.6) also estimated values of initial fishing mortality that were consistently higher than the priors, indicating the priors were constraining the upper range of the parameter estimates. Despite the differences in the initial fishing mortality rates, the alternative models estimated very similar initial biomass levels and virtually identical biomass trajectories (Figure 9). This was attributable to differences in the estimates of the recruitment deviates in the initial years (1987–1990) for three model options; higher initial fishing mortality rates were associated with higher recruitment deviates in the initial years.

The model estimated cyclical patterns in recruitment over 3–5 year periods with an increasing trend in recruitment from the late 2000s. Average recruitment from 2012 to 2020 was estimated to have been 2.6 times greater than during 1987–2007 (Figure 8). However, estimates of recent (2017–2020) recruitments are highly uncertain.

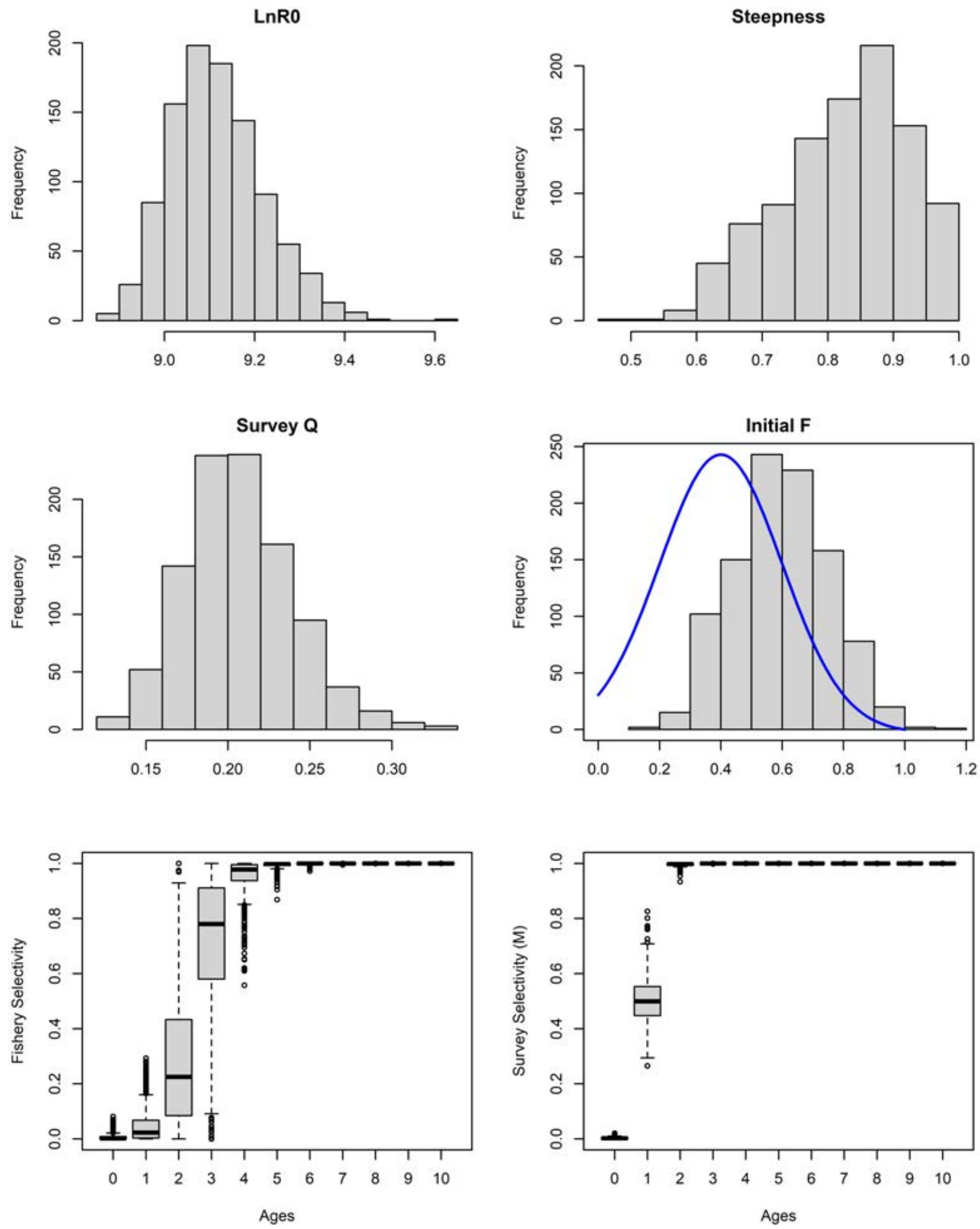

Figure 7: Estimates of posterior distributions of model parameters and selectivity functions from the base model MCMCs. The blue line represents the prior for the initial fishing mortality parameter.

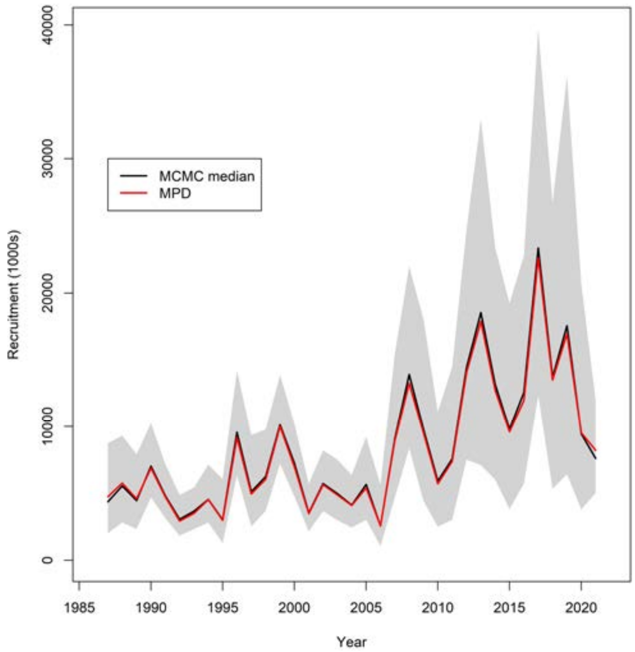

Figure 8: Annual recruitment for the base model. Recruitment deviates were estimated for 1987–2020. The black line represents the median and the shaded area represents the 95% credible interval. The red line represents the MPD estimates.

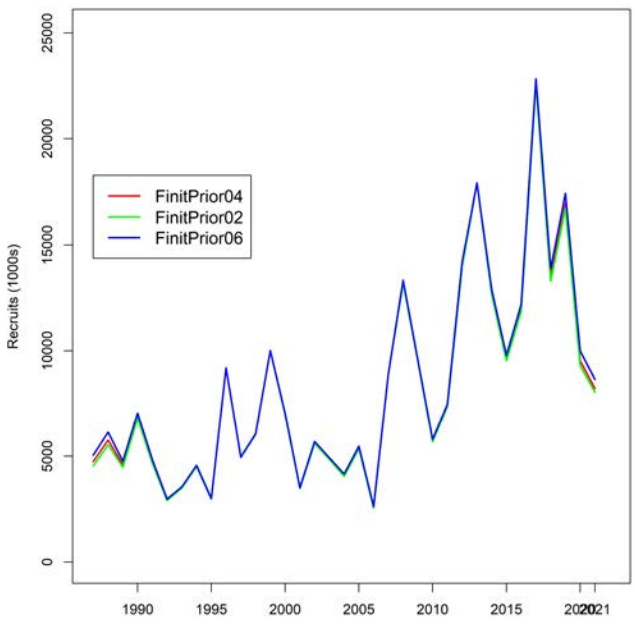

Figure 9: A comparison of the estimates of annual recruitment for three model options with different priors for the initial (1987) level of fishing mortality (normal priors with a mean of 0.2, 0.4, or 0.6),

3.2.2 Fit to observational data

For the base model option, the model provided a very good fit to the time series of trawl survey biomass indices, with the exception of the 2003 trawl survey index (Figure 10). The model fits the large increase in the trawl survey indices between 2009 and 2015 as well as the high biomass indices from the three subsequent surveys (2017, 2019, and 2021).

The model also provided a good fit to the associated age and length composition data (Figure 11 and Figure 12). A notable exception was the over-estimation of the proportion of two year old fish in the 2003 survey age composition. This may indicate that the lower catchability of the 2003 trawl survey (and low biomass index) was related to a lower availability of the younger (1–2 year old) fish to the survey.

Overall, the model approximates the modal structure of the trawl survey length compositions, although the fit to the 2021 female length composition was poor with the strong mode at about 35 cm (T.L.) under-estimated by the model. There was also an over-estimation of the proportion of larger male fish from the 2019 and 2021 surveys (Figure 12).

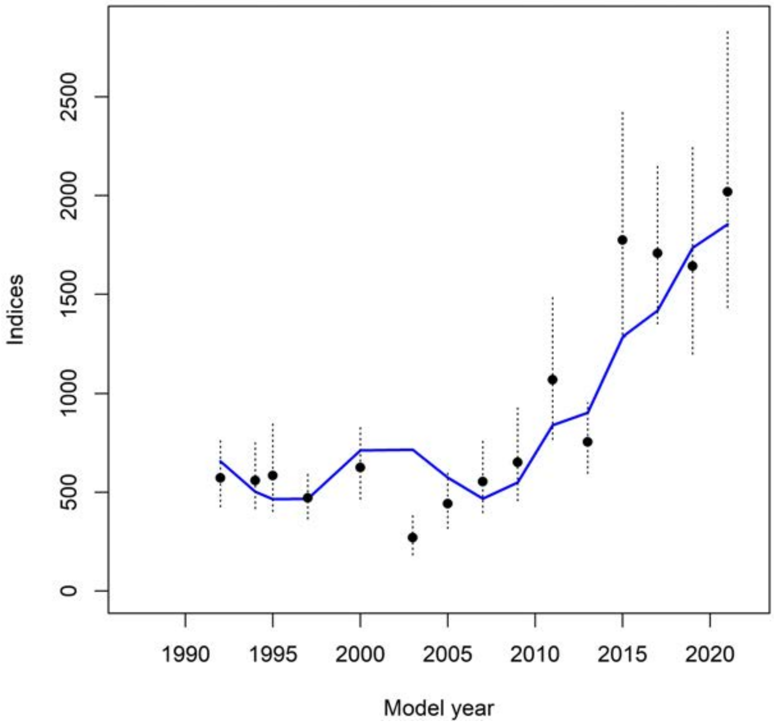

Figure 10: The fit (MPD) to the trawl survey biomass indices (points) for the base model option.

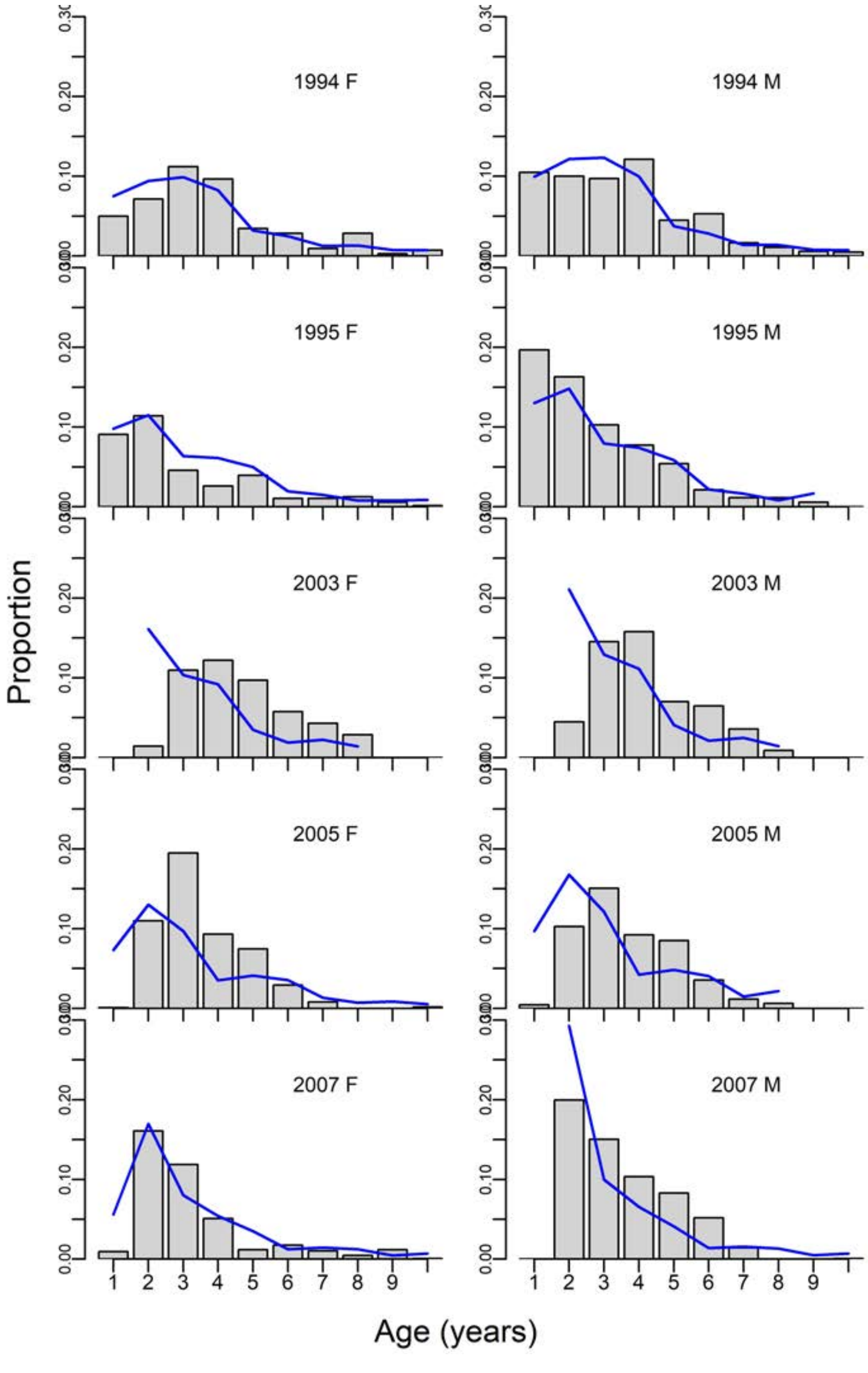

Figure 11: Observed (grey bars) and predicted (blue lines) proportions-at-age for females (left) and males (right) for the 1994, 1995, 2003, 2005, and 2007 *Kaharoa* WCSI trawl surveys. The oldest age class includes fish 10 years and older ('plus group').

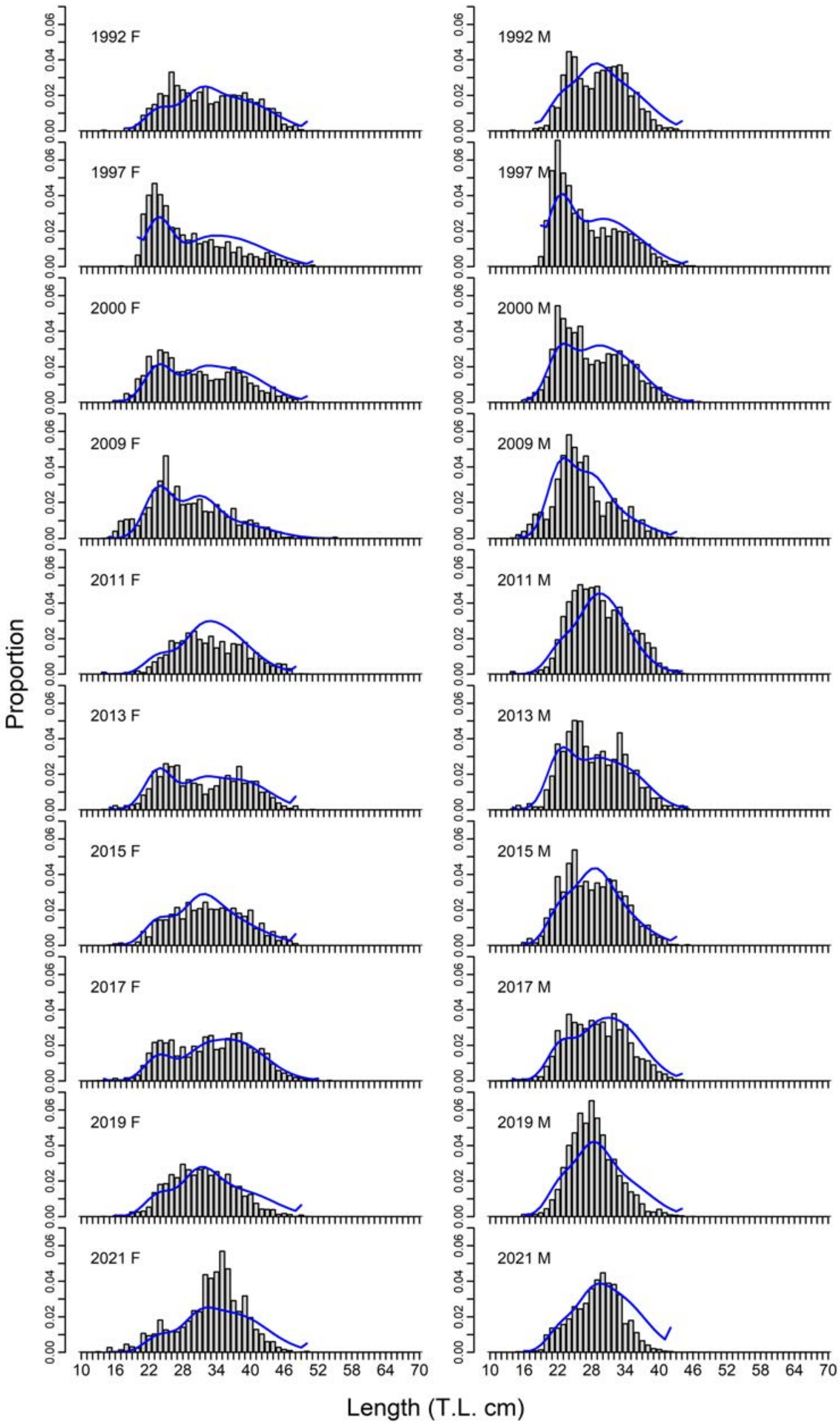

Figure 12: Observed (grey bars) and predicted (blue lines) proportions-at-length for females (left) and males (right) from the time series of *Kaharoa* WCSI trawl surveys. The length compositions from the surveys with age composition data were not included in the model.

3.2.3 Model sensitivity analyses

During model development, a wide range of model options were evaluated to investigate key model assumptions. The sensitivities included lower (0.25) and higher (0.35) values of natural mortality (compared with 0.31), the prior on the initial (1987) level of fishing mortality, varying the selectivity of the commercial fishery, and a set of models contrasting the influence of the trawl survey biomass indices and length/age composition data (Table 5). The sensitivities were implemented as single changes from the base model.

Table 5: Description of model options and sensitivities.

Model option	Description
Base	Base model option.
Mlow	Natural mortality *M* 0.25 for males and females.
Mhigh	Natural mortality *M* 0.35 for males and females.
Finit02	Prior on Initial (1987) fishing mortality Normal(0.2, 0.2).
Finit06	Prior on Initial (1987) fishing mortality Normal(0.6, 0.2).
FisherySelect	Fishery logistic length-based selectivity, 50% at 25 cm, 100% at 30 cm.
FisherySelect2	Fishery knife-edge selectivity at 30 cm (T.L.).
DwtAge	Down weight age composition data (ESS = 10).
DwtLength	Down weight length composition data (ESS = 10).
TSurveyError	Include additional process error 0.10

Overall, the MPD results (Table 6) were comparable to the median MCMC values (Table 7). For all model options, current stock status was estimated to be at or above *SB0* and fishing mortality was estimated to be well below $F_{SB40\%}$.

Changing the prior for the initial (1987) levels of fishing mortality did not appreciably change the overall model estimates of current stock status and yield (Table 6). Reducing the age (and length) of the selectivity of the commercial fishery resulted in slightly less optimistic estimates of current stock status and lower estimates of current yield. Similarly, reducing natural mortality resulted in a slightly less optimistic estimate of stock status.

Decreasing the weighting on the trawl survey age composition data reduced the overall magnitude of recruitment, especially from 2008 onwards. Consequently, the magnitude of the increase in spawning biomass was lower during the following period, and hence estimates of current stock status and yield were less optimistic (Table 6). Reducing the precision on the trawl survey biomass indices also resulted in a slightly less optimistic estimate of stock status.

Table 6: MPD estimates of key stock status indicators for the range of model options. Estimates of current potential yields (t) are the yield from applying the $F_{SB40\%}$ level of fishing mortality to the current biomass.

Model option	SB_0 (t)	SB_{2021}/SB_0	$F_{2021}/F_{SB40\%}$	Current yield (t)
Base	4 500	1.126	0.474	2 496
Mlow	4 554	0.880	0.677	1 696
Mhigh	4 724	1.282	0.374	3 197
Finit02	4 409	1.145	0.467	2 567
Finit06	4 733	1.090	0.485	2 407
FisherySelect	4 767	0.934	0.617	1 675
FisherySelect2	4 383	1.044	0.542	2 009
DwtAge	4 399	0.830	0.728	1 443
DwtLength	4 909	1.063	0.500	2 199
TSurveyError	3 968	0.926	0.621	1 898

3.3 Stock status

For the base model and the range of model sensitivities, biomass was estimated to have increased considerably from 2010 and current (2021) stock status was estimated to be at about the equilibrium, unexploited level (i.e., SB_0) (Table 7, Figure 13). For all model options, current rates of fishing mortality were estimated to be well below the fishing mortality threshold ($F_{SB40\%}$) (Table 7, Figure 14).

Estimates of equilibrium and current yield were derived based on the $F_{SB40\%}$ fishing mortality rate (Table 8). Equilibrium yields were estimated to be about 800–1000 t per annum. $F_{SB40\%}$ yields from 2020/21 biomass levels were estimated to be substantially higher than the equilibrium yields (about 2000–3000 t), although the yield estimates are uncertain.

Table 7: Estimates of current (2020/21) and virgin spawning biomass (t) (median and the 95% confidence interval from the MCMCs) and probabilities of current biomass being above specified levels and probability of fishing mortality being below the level of fishing mortality associated with the threshold level.

Model option	SB_0	SB_{2021}	SB_{2021}/SB_0	**Pr(SB_{2021} > X% SB_0)**		
				35%	**20%**	**10%**
Base	4 990	5 528	1.108	1.00	1.00	1.00
	(4 226–6 247)	(3 779–7 919)	(0.799–1.44)			
DwtAge	4 849	4 816	0.986	1.00	1.00	1.00
	(3 966–6 572)	(3 093–7 859)	(0.69–1.356)			
DwtLength	5 413	6 023	1.118	1.00	1.00	1.00
	(4 373–7 301)	(3 944–9 428)	(0.776–1.52)			
Finit06	5 215	5 633	1.091	1.00	1.00	1.00
	(4 349–6 564)	(3 970–8 174)	(0.788–1.408)			
Finit02	4 933	5 528	1.125	1.00	1.00	1.00
	(4 217–6 131)	(3 832–7 914)	(0.804–1.457)			
Mhigh	5 365	6 830	1.262	1.00	1.00	1.00
	(4 318–7 346)	(4 369–10 504)	(0.921–1.605)			
Mlow	4 939	4 369	0.885	1.00	1.00	1.00
	(4 313–5 981)	(3 045–6 070)	(0.63–1.147)			
TSurveyError	4 421	4 034	0.901	1.00	1.00	1.00
	(3 772–5 411)	(2 499–6 482)	(0.616–1.297)			

	$F_{SB40\%}$	$F_{2021}/F_{SB40\%}$	**Pr($F_{2021} < F_{SB40\%}$)**
Base	0.2248	0.44	1.00
		(0.296–0.686)	
DwtAge	0.2102	0.543	1.00
		(0.327–0.845)	
DwtLength	0.2167	0.429	1.00
		(0.269–0.702)	
Finit06	0.2186	0.441	1.00
		(0.299–0.675)	
Finit02	0.2267	0.44	1.00
		(0.294–0.691)	
Mhigh	0.2342	0.342	1.00
		(0.219–0.551)	
Mlow	0.2016	0.624	0.99
		(0.447–0.908)	
TSurveyError	0.2298	0.593	0.98
		(0.359–0.957)	

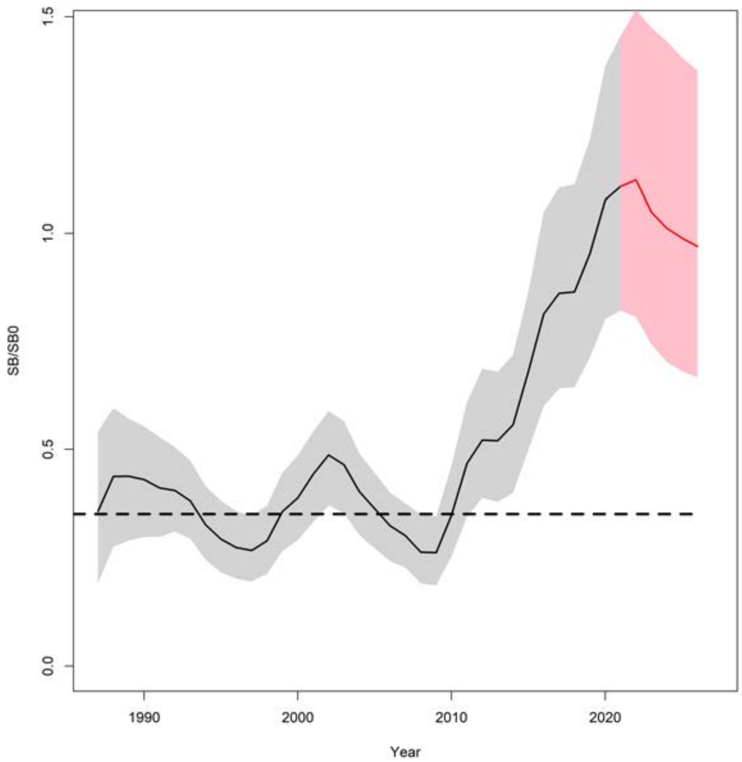

Figure 13: Annual trend in spawning biomass relative to the equilibrium unexploited level (*SB₀*) for the base model. The line represents the median and the shaded area represents the 95% confidence interval. The projection period (2022–2026) is in red. The dashed line represents the 35% *SB₀* interim target biomass level.

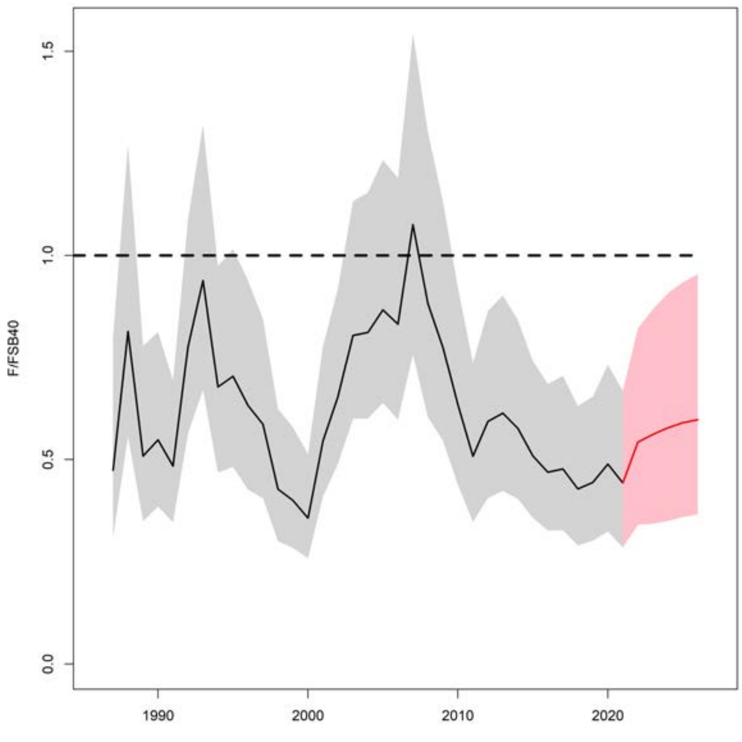

Figure 14: Annual trend in fishing mortality relative to the $F_{SB40\%}$ interim threshold level for the base model. The line represents the median and the shaded area represents the 95% credible interval. The projection period (2022–2026) is in red. The dashed line represents the interim fishing mortality threshold.

Table 8: Estimates of equilibrium yield (t) at $F_{SB40\%}$ at equilibrium and at the 2020/21 biomass levels for the base model and the model sensitivities. The values represent the median and the 95% confidence interval from the MCMCs.

Model option	$F_{SB40\%}$	
	Yield at 40% B_0	Yield at current biomass
Base	953 (811–1 149)	2 748 (1 609–4 681)
DwtAge	859 (744–1 070)	2 087 (1 234–3 792)
DwtLength	989 (815–1 277)	2 688 (1 515–5 117)
Finit06	960 (832–1 162)	2 723 (1 627–4 711)
Finit02	952 (808–1 160)	2 750 (1 583–4 957)
Mhigh	1 105 (891–1 453)	3 621 (1 964–6 547)
Mlow	807 (726–906)	1 875 (1 163–2 819)
TSurveyError	861 (749–1 043)	2 020 (1 094–3 934)

For the base model, stock projections were conducted for the 5-year period following the terminal year of the model (i.e., 2022–2026). Future recruitments were resampled from the average level of recent recruitment (2011–2020), with variation equivalent to *sigmaR*. Commercial catches in the projection period were held constant at the current TACC of 1298 t. There was no explicit allowance for unreported commercial catch, recreational catch, or customary catch. Stock abundance was predicted to decline during the projection period, although the biomass remains at about the SB_0 reference level throughout the period (Figure 13, Table 9).

Table 9: Estimates of projected (2025/26) spawning biomass (t) (median and the 95% confidence interval from the MCMCs) and probability of the spawning biomass being above default biomass limits and the interim threshold level in 2026 from the base model projections.

Model option	SB_{2026}/SB_0	$Pr(SB_{2026} > X\% \, SB_0)$		
		35%	20%	10%
Base	0.969 (0.667–1.376)	1.00	1.00	1.00

4. MANAGEMENT PROCEDURES

A range of management procedures were developed for GUR 7 based on the empirical linear relationship derived between the WCSI trawl survey biomass indices and the corresponding annual reported commercial catch (Figure 15). The relationship was forced through the origin to ensure catches were aligned with low survey biomass levels. The relationship provides a moderate fit to the observed data, although there is a subset of records with a higher catch than predicted from the linear model (Figure 15).

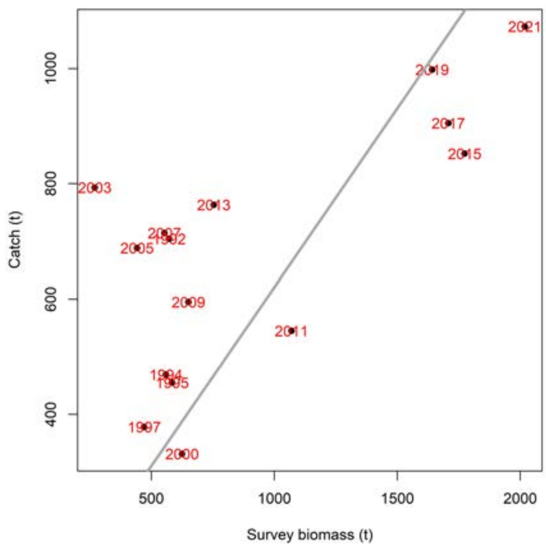

Figure 15: The relationship between red gurnard WCSI trawl survey biomass indices and GUR 7 commercial catch from the corresponding fishing year. The grey line represents the linear relationship constrained to the origin (zero intercept). The slope of the line is denoted *F*proxy.

Conceptually, the relationship represents a constant level of fishing mortality (denoted '*F*proxy'). The simplest (*base*) set of management procedures determined the TACC from the slope coefficient (*F*proxy) using a range of scalars (0.8, 1.0, 1.2….2.0, 2.5) (Equation 1); i.e., varying the magnitude of the constant level of fishing mortality (Figure 16). More complex management procedures incorporated declining levels of fishing mortality below threshold levels of the observed trawl survey biomass indices, with inflection points at the lower quartile (*Fslope*), median (*Fslope2*) or upper quartile (*Fslope3*) (Figure 16).

$TACC_{(year + 1,\ year + 2)} = Scalar * F proxy * TrawlSurveyBiomass_{year}$ Equation 1

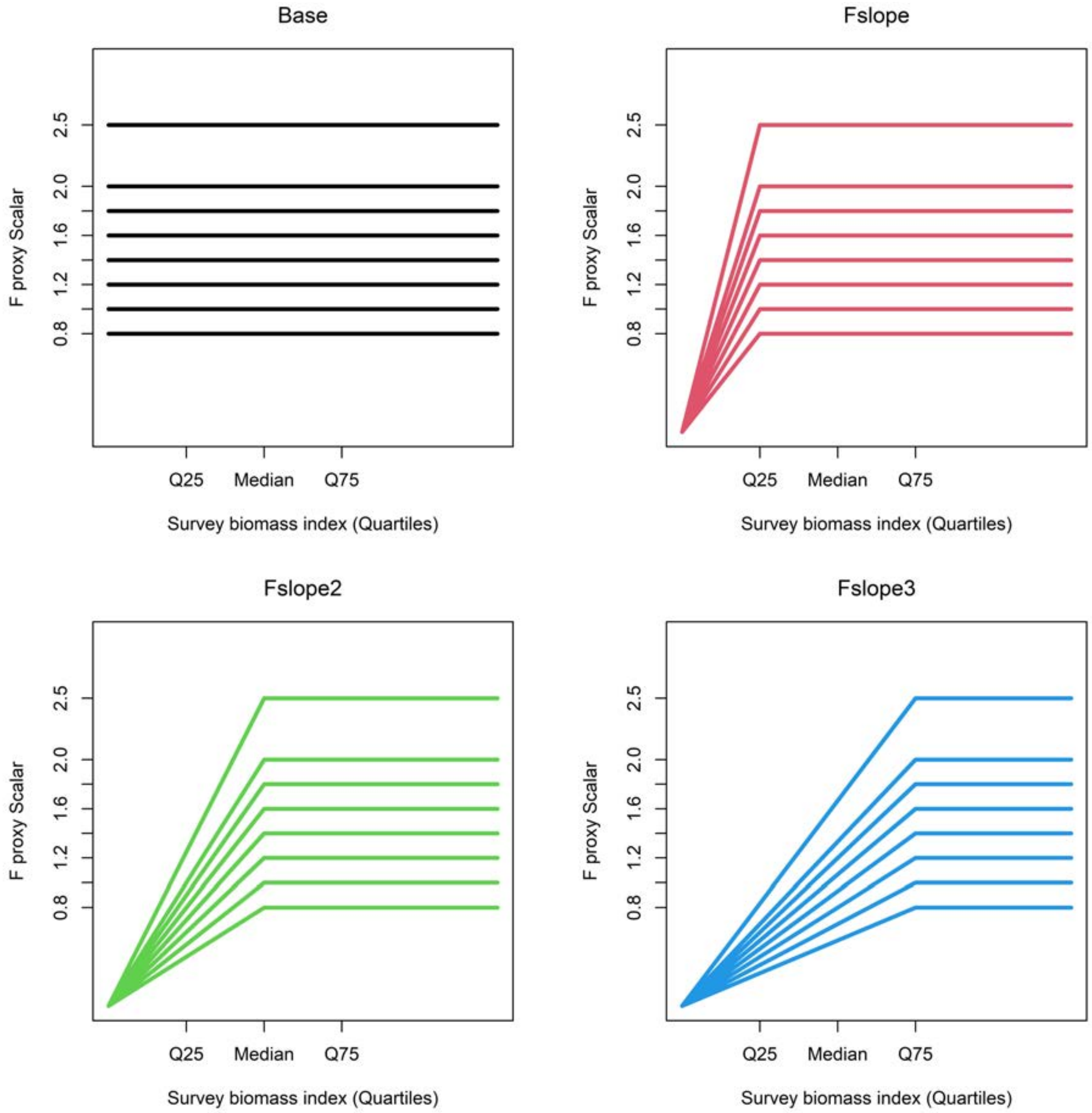

Figure 16: The range of scalars applied to the *F* proxy value in the suite of Management Procedures. The different functional forms of the scalars have inflection points at different levels of trawl survey biomass from the reference data set (15 surveys).

Simulation-testing of the management procedures was carried out using the MCMC output from the 2022 GUR 7 assessment model (base model and *Mlow* sensitivity). The individual (1000) MCMC samples were used to initialise the population age structure and projections were conducted over 100 years with recruitment resampled from the estimated recruitment deviates. Simulated trawl survey biomass indices (with CV of 17%) were generated biennially during the projection period and the specific management procedure was applied to set the TACC for the next two years following each trawl survey (conducted in March–April).

Constraints were applied to investigate the effect of limiting the scale of the changes in the TACC (maximum change of ± 20% or ± 50%). Annual catches were taken at the level of the TACC up to a maximum exploitation rate of 50%. The exploitation rate constraint was imposed to maintain the simulated biomass above zero.

Two alternative periods were applied to define the projected recruitments: the entire recruitment model estimation period (All, 1987–2020) and the lower recruitment period 1987–2007 (low). The

MPs were also tested with different levels of autocorrelation between annual recruitments and additional process error associated with the trawl survey biomass estimates.

The performance of the individual management procedures, summarised across the 1000 simulations, was assessed based on the median biomass ratio relative to SB_0, the proportion of years below 20% and 10% of the SB_0 level, average annual catch, and the standard deviation of annual catches. The frequency of TACC changes and the frequency of years when the maximum exploitation rate was attained were also summarised. Few scenarios attained the maximum exploitation rate in more the 5% of the years and those scenarios also had a higher probability (greater than 10%) of reducing the biomass below 20% SB_0 and, hence, were discounted.

For the base set of MPs, increasing the scalar value resulted in a lower level of spawning biomass relative to the unexploited equilibrium level (SB_0) (Figure 17, Appendix 3, Table A4). For comparative purposes, a constant fishing mortality rate of $F_{SB40\%}$ was also applied to the simulated populations. Relatively high values of the scale parameter (1.8–2.0) were required to achieve average catches comparable with $F_{SB40\%}$ (Figure 17, Appendix 3, Table A7) and resulted in considerable variation in the annual catches (Figure 17, Appendix 3, Table A8). The highest scale parameter (2.5) yielded average annual catches that slightly exceeded the $F_{SB40\%}$ based catches and resulted in higher probability of the stock declining below 20% SB_0 (Figure 17, Appendix 3, Table A5).

Overall, the performance of the base MP was relatively insensitive to the magnitude of the maximum TACC change (20% or 50%). MP performance was also relatively insensitive to the level of autocorrelation in recruitment and the inclusion of additional process error in the trawl survey biomass indices (Appendix 3).

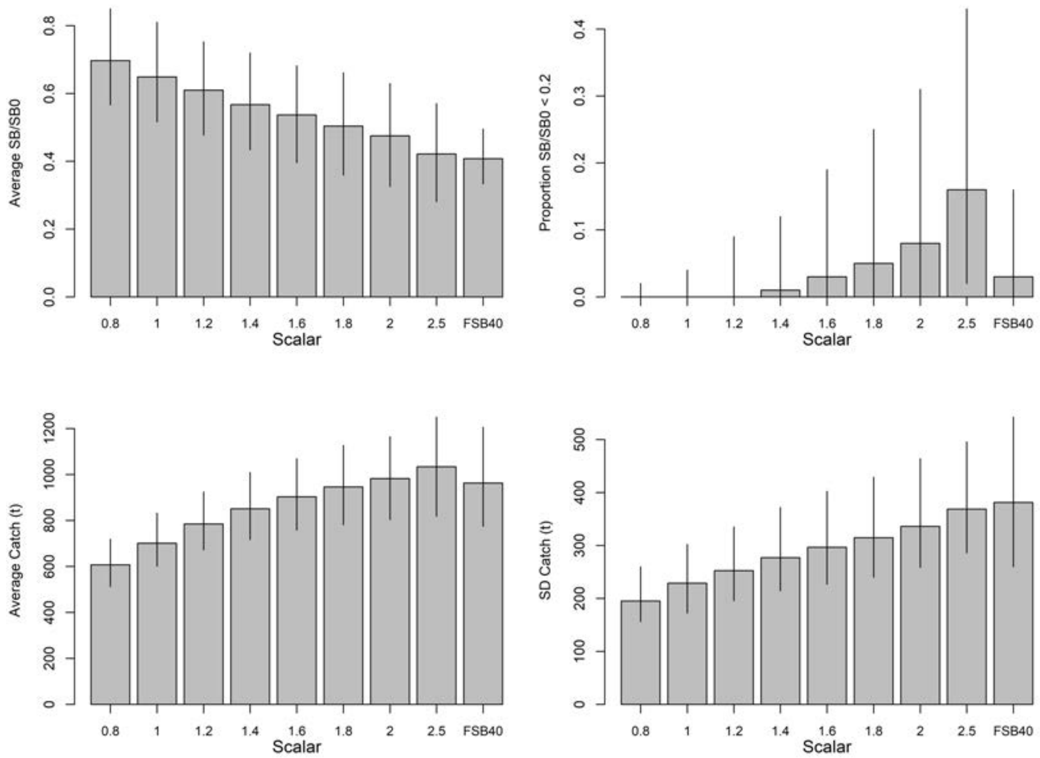

Figure 17: A comparison of the performance of different scalars applied to the base (constant) MP (with a maximum change in TACC of 20%, no additional trawl survey process error, resampling from <u>all</u> recruitment deviates and recruitment autocorrelation 0.3).

There were some differences in the performance of the MP that included more complex relationships between trawl survey biomass and *F*proxy (i.e., inflection points at different biomass levels) (Figure 18). The *Fslope3* MP was more conservative than the other three options, resulting in lower average annual catches and, correspondingly, higher average biomass levels.

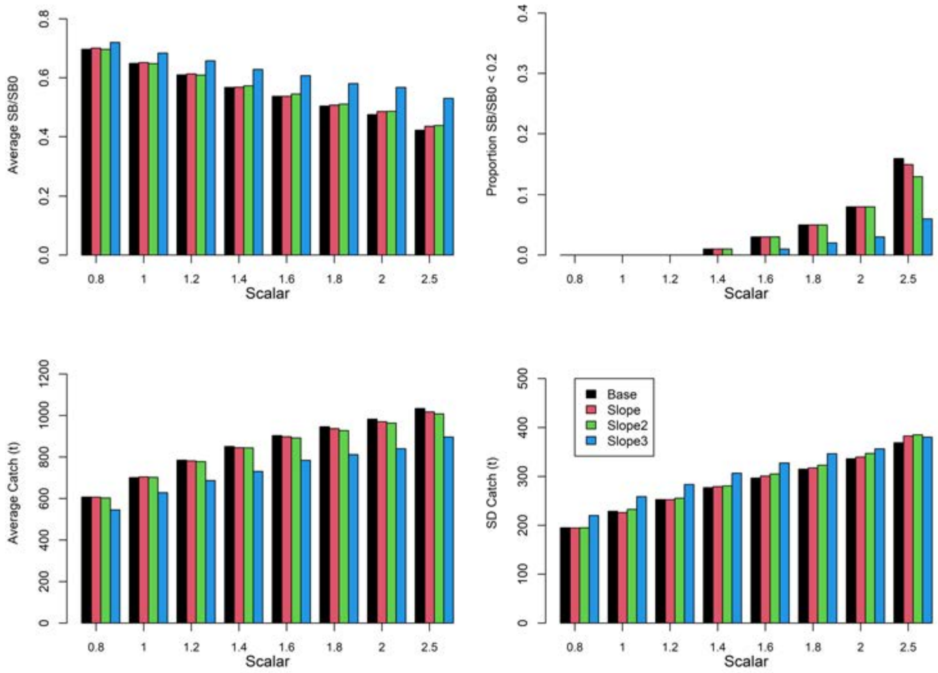

Figure 18: A comparison of the performance indicators of different MPs and scalars (with a maximum change in TACC of 20%, no additional trawl survey process error, resampling from <u>all</u> recruitment deviates and recruitment autocorrelation 0.3).

If recruitment was to revert to the lower (1987–2007) level, fishing the stock at a level approaching F_{SB40} would result in biomass fluctuating about the 30% SB_0 level and an increased probability of the stock declining below the soft limit. For the lower recruitment level, there was more contrast in the performance of the alternative MPs (Figure 19) with the *Fslope3* MP maintaining the stock well above the 20% SB_0 soft limit for all scenarios, with a larger associated reduction in catch compared with the other MPs.

Similarly, for a stock with a lower level of natural mortality, the corresponding set of MPs resulted in a lower level of biomass (Figure 20) relative to the results from the base assessment model (Figure 17). For scalar values of 1.8–2.0, the stock would fluctuate about the 35% SB_0 target biomass level, although there is an increased probability of declining below the 20% SB_0 level, indicating that an MP scalar of 1.6 is more appropriate (Figure 20).

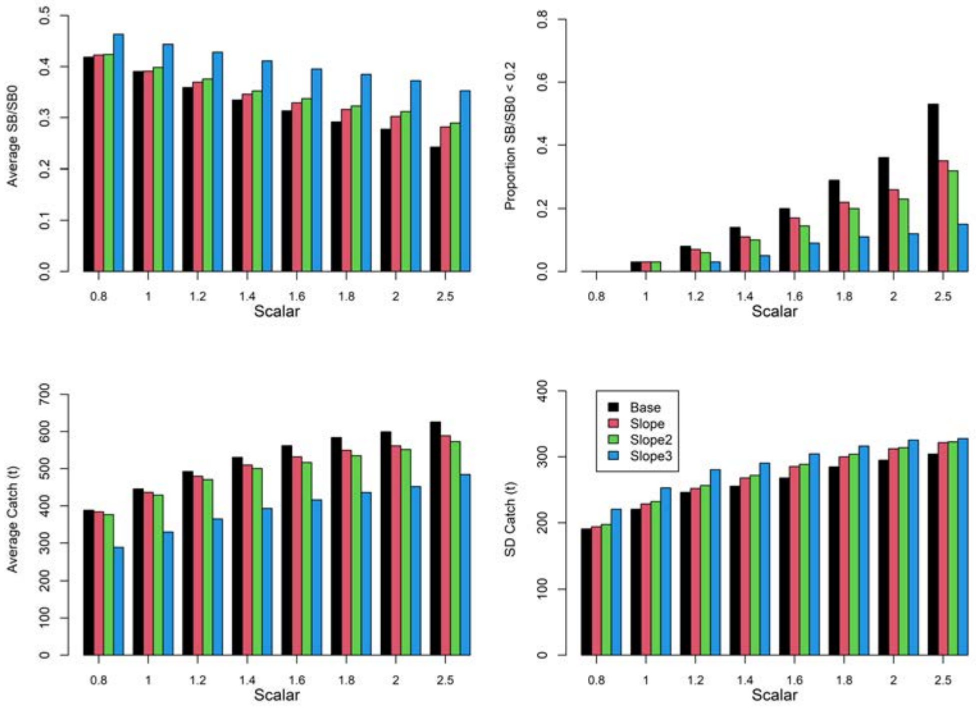

Figure 19: A comparison of the performance of different MPs and scalars (with a maximum change in TACC of 20%, no additional trawl survey process error, resampling from <u>low</u> recruitment deviates, and recruitment autocorrelation 0.3).

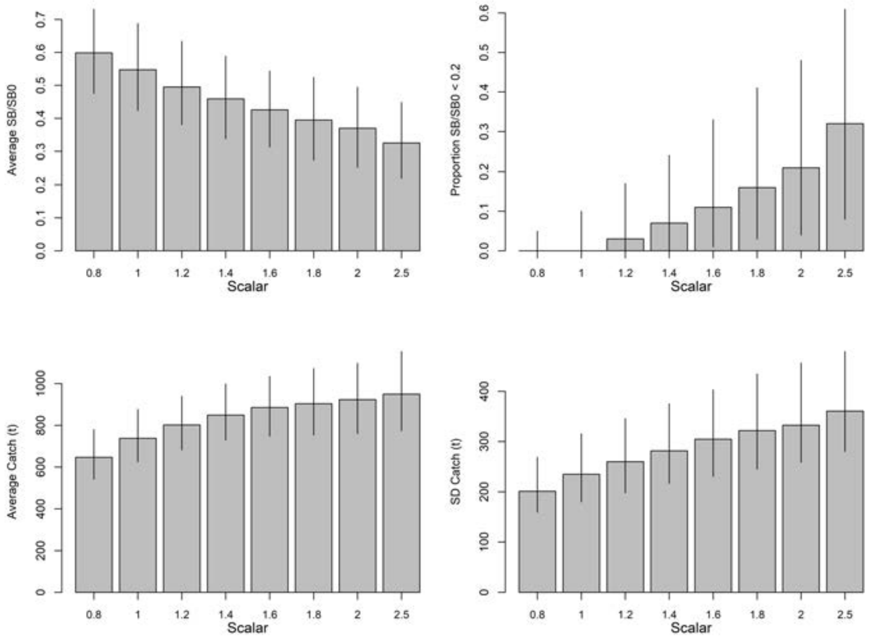

Figure 20: A comparison of the performance of different scalars applied to the base (constant) MP for the *Mlow* sensitivity (with a maximum change in TACC of 20%, no additional trawl survey process error, resampling from <u>all</u> recruitment deviates, and recruitment autocorrelation 0.3).

Overall, the results of the MP evaluation indicated that a scalar of 1.6–2.0 would yield results that were consistent with fishing the stock at the $F_{SB40\%}$ level, maintaining the stock at or above the HSS default target biomass level of 35% SB_0 (moderate productivity) and well above the 20% SB_0 soft limit. For the main set of simulations, the performance of the MP did not appreciably improve with declining levels of fishing mortality at lower biomass levels. However, under scenarios of lower overall productivity, the more complex MPs were more conservative and maintained the stock well above the soft limit.

Since 2008, recruitment has been maintained at a considerably higher overall level. Hence, there is no strong justification for selecting an MP based on the performance at low recruitment levels. Future recruitment levels would continue to be monitored via the trawl survey and the MP could be modified if a sustained period of lower recruitment was observed (via a breakout rule).

5. DISCUSSION

The stock assessment estimated that the biomass of red gurnard increased substantially (by about 350%) during the 2010s following a general increase in recruitment from 2008 onwards. Age composition data are not available from recent surveys to provide more direct observations of recruitment strengths during this period. However, the increase in recruitment is consistent with the substantial (3–4 fold) increase in the trawl survey biomass indices for smaller (less than 30 cm T.L.) red gurnard from 2007 (MacGibbon et al. 2022).

The recent increase in recruitment has corresponded with a general increase in sea surface temperatures (SST) off the west coast of the South Island (NIWA 2022), with positive SST anomalies for 2006–2021 and exceptionally high sea temperatures in the summers of 2017/18 and 2021/22. This contrasted with a period of lower SST during the early-mid 1990s (NIWA 2022). These changes in the prevailing oceanographic conditions may have contributed to the increased productivity of the stock from the mid-2000s.

There are similarities between the increase in red gurnard recruitment and recent trends in the recruitment of snapper (SNA 7) in TBGB (Langley 2021). For both species, recruitment was estimated to have been low during the 1990s and early 2000s. The initial strong recruitment of red gurnard in 2007/08 corresponded with the very strong snapper recruitment (2007 year class). Very strong recruitment was also estimated for snapper in 2010, 2017, and 2018. Strong recruitment was estimated for red gurnard for the two latter years. Overall, there is a moderate correlation between the 1987–2020 recruitment deviates from the GUR 7 and SNA 7 assessment models (corr. coef 0.63). This may indicate that the productivity of both species has increased following a shift in prevailing environmental conditions over the last 10–15 years.

There is considerable uncertainty associated with the estimates of recent recruitment (year class strengths). Red gurnard otoliths have routinely been collected from WCSI trawl surveys. Estimates of recent recruitment would be improved through the derivation of age compositions from the trawl surveys, particular for the most recent surveys. Lyon & Horn (2011) observed that estimated growth rates of red gurnard (2–3 years) were much faster from the 1994 and 1995 surveys (Sutton 1997) compared with the 2003–2007 surveys. The difference in growth rates between the two studies was attributed to either inter-annual variability in the growth rates of juvenile red gurnard or discrepancies in the ageing of 1–2 year old fish (Lyon & Horn 2011). Additional sets of ageing data from recent surveys would provide a comparison with the growth rates derived from the earlier surveys. The study should also be extended to re-age the earlier otolith collections to confirm the previous results. Further comparisons of the age structure of red gurnard between TBGB and WCSI may strengthen the understanding of the linkages between the two areas (Lyon & Horn 2011, Morrison et al. 2014).

There are no direct observations of the length or age composition of the catch from the commercial fishery and catches were assumed to be predominantly composed of fish larger than 30 cm (T.L.). Model trials included a range of plausible alternative selectivity functions for the commercial fishery, indicating assessment results were relatively insensitive to the selectivity assumptions. Nonetheless, catch sampling is required to determine the length/age composition of the catch from the GUR 7 trawl fisheries and inform the model regarding the selectivity of the constituent fisheries, spatially stratified to include the WCSI and TBGB areas. There may also have been changes in the fishery selectivities over time, related to operational changes such as the retention of smaller red gurnard and changes in mesh size of trawl gear.

The 2022 GUR 7 stock assessment was accepted by the May 2022 Fishery Assessment Plenary. The biennial *Kaharoa* WCSI inshore trawl survey will provide ongoing monitoring of the abundance of red gurnard. The next trawl survey is scheduled for March–April 2023.

A range of potential Management Procedures were evaluated that directly applied the WCSI trawl survey biomass estimates to determine the GUR 7 TACC for the subsequent two years. The implementation of such an MP would enable a more responsive management approach to the fishery, particularly given the scale of the variation in red gurnard abundance. Further consultation is required between Fisheries New Zealand and key stakeholders to determine the most appropriate MP for the GUR 7 fishery and formulate an associated management plan to mitigate factors that may compromise the performance of the MP ('break out' rules). Such factors may include a sustained period of low recruitment observed from recent trawl surveys, postponement of a scheduled trawl survey, and/or a sustained period of lower than anticipated catch from the fishery.

6. ACKNOWLEDGEMENTS

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APPENDIX 1: MODEL INPUT DATA SETS

Table A1: Annual red gurnard commercial catch (t) included in the assessment mode1. Years are specified as model years and are denoted by the year at the start of the fishing year (e.g. 1987 is the 1986/87 fishing year).

Year	Catch	Year	Catch
1987	421	2005	688
1988	806	2006	604
1989	479	2007	714
1990	511	2008	563
1991	442	2009	595
1992	704	2010	603
1993	761	2011	545
1994	469	2012	684
1995	455	2013	763
1996	382	2014	837
1997	378	2015	852
1998	309	2016	852
1999	323	2017	905
2000	331	2018	882
2001	571	2019	998
2002	686	2020	1 182
2003	793	2021	1 073
2004	717		

Table A2: Proportional age compositions of female and male red gurnard from the *Kaharoa* WCSI trawl surveys. The oldest age class represents an accumulated age class (plus group).

Age					Females					Males
(yr)	1994	1995	2003	2005	2007	1994	1995	2003	2005	2007
1	0.0500	0.0907	0.0000	0.0009	0.0095	0.1050	0.1969	0.0000	0.0044	0.0000
2	0.0714	0.1139	0.0144	0.1098	0.1607	0.1000	0.1632	0.0449	0.1027	0.1997
3	0.1121	0.0457	0.1095	0.1949	0.1185	0.0971	0.1027	0.1454	0.1506	0.1504
4	0.0964	0.0260	0.1221	0.0930	0.0509	0.1214	0.0774	0.1580	0.0921	0.1034
5	0.0343	0.0394	0.0969	0.0744	0.0119	0.0450	0.0541	0.0700	0.0850	0.0827
6	0.0286	0.0105	0.0575	0.0292	0.0175	0.0529	0.0211	0.0646	0.0354	0.0517
7	0.0093	0.0105	0.0431	0.0080	0.0103	0.0164	0.0113	0.0359	0.0115	0.0143
8	0.0286	0.0127	0.0287	0.0000	0.0048	0.0107	0.0113	0.0090	0.0062	0.0000
9	0.0029	0.0056	0.0000	0.0000	0.0119	0.0057	0.0056	0.0000	0.0000	0.0000
10	0.0071	0.0014	0.0000	0.0018	0.0008	0.0050	0.0000	0.0000	0.0000	0.0008

Table A3a: Length frequency distributions of red gurnard from the *Kaharoa* WCSI trawl survey. The years represent model years.

Lgth (cm)	Female					Male				
	1992	1997	2000	2009	2011	1992	1997	2000	2009	2011
10	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
11	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
12	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
13	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
14	0.0004	0.0000	0.0000	0.0001	0.0011	0.0004	0.0000	0.0000	0.0003	0.0015
15	0.0000	0.0000	0.0000	0.0006	0.0001	0.0000	0.0000	0.0000	0.0022	0.0004
16	0.0000	0.0000	0.0010	0.0041	0.0004	0.0000	0.0000	0.0012	0.0040	0.0005
17	0.0000	0.0003	0.0011	0.0098	0.0004	0.0000	0.0000	0.0027	0.0080	0.0011
18	0.0016	0.0000	0.0049	0.0107	0.0010	0.0013	0.0003	0.0055	0.0134	0.0015
19	0.0018	0.0000	0.0040	0.0109	0.0013	0.0017	0.0056	0.0070	0.0144	0.0024
20	0.0038	0.0065	0.0131	0.0073	0.0018	0.0031	0.0259	0.0143	0.0107	0.0039
21	0.0088	0.0295	0.0150	0.0136	0.0009	0.0140	0.0539	0.0298	0.0175	0.0089
22	0.0127	0.0402	0.0258	0.0171	0.0040	0.0131	0.0710	0.0543	0.0331	0.0194
23	0.0149	0.0468	0.0204	0.0268	0.0069	0.0314	0.0526	0.0471	0.0464	0.0324
24	0.0209	0.0405	0.0294	0.0320	0.0092	0.0446	0.0456	0.0418	0.0580	0.0407
25	0.0198	0.0342	0.0281	0.0462	0.0109	0.0416	0.0300	0.0392	0.0510	0.0471
26	0.0331	0.0221	0.0250	0.0247	0.0188	0.0294	0.0321	0.0428	0.0425	0.0503
27	0.0255	0.0215	0.0170	0.0290	0.0176	0.0252	0.0260	0.0246	0.0461	0.0479
28	0.0231	0.0178	0.0172	0.0187	0.0187	0.0238	0.0203	0.0212	0.0287	0.0487
29	0.0213	0.0148	0.0181	0.0192	0.0231	0.0329	0.0164	0.0235	0.0206	0.0494
30	0.0171	0.0186	0.0157	0.0194	0.0242	0.0341	0.0218	0.0223	0.0126	0.0413
31	0.0218	0.0129	0.0173	0.0218	0.0196	0.0357	0.0171	0.0272	0.0199	0.0318
32	0.0251	0.0140	0.0155	0.0149	0.0174	0.0362	0.0212	0.0267	0.0221	0.0360
33	0.0152	0.0151	0.0122	0.0146	0.0213	0.0371	0.0198	0.0289	0.0169	0.0377
34	0.0162	0.0112	0.0129	0.0187	0.0148	0.0326	0.0195	0.0209	0.0101	0.0287
35	0.0197	0.0108	0.0129	0.0149	0.0183	0.0196	0.0183	0.0234	0.0176	0.0228
36	0.0202	0.0139	0.0169	0.0120	0.0117	0.0216	0.0150	0.0212	0.0097	0.0245
37	0.0202	0.0080	0.0198	0.0166	0.0171	0.0123	0.0134	0.0119	0.0104	0.0228
38	0.0198	0.0109	0.0166	0.0075	0.0166	0.0109	0.0125	0.0107	0.0042	0.0176
39	0.0214	0.0058	0.0144	0.0095	0.0178	0.0063	0.0072	0.0083	0.0056	0.0149
40	0.0179	0.0071	0.0107	0.0103	0.0088	0.0032	0.0052	0.0083	0.0043	0.0062
41	0.0160	0.0055	0.0093	0.0086	0.0120	0.0017	0.0031	0.0040	0.0034	0.0039
42	0.0179	0.0043	0.0064	0.0064	0.0086	0.0018	0.0011	0.0018	0.0008	0.0023
43	0.0128	0.0078	0.0054	0.0062	0.0063	0.0011	0.0009	0.0005	0.0004	0.0022
44	0.0126	0.0063	0.0086	0.0042	0.0047	0.0001	0.0016	0.0013	0.0002	0.0006
45	0.0103	0.0042	0.0034	0.0038	0.0059	0.0002	0.0004	0.0000	0.0000	0.0002
46	0.0038	0.0036	0.0041	0.0006	0.0056	0.0000	0.0004	0.0002	0.0002	0.0000
47	0.0023	0.0025	0.0025	0.0008	0.0031	0.0000	0.0000	0.0004	0.0000	0.0000
48	0.0032	0.0018	0.0017	0.0016	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000
49	0.0007	0.0019	0.0000	0.0002	0.0003	0.0002	0.0000	0.0000	0.0000	0.0000
50	0.0001	0.0003	0.0003	0.0002	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000
51	0.0002	0.0008	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
52	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
53	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
54	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
55	0.0000	0.0000	0.0000	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table A3b: Length frequency distributions of red gurnard from the *Kaharoa* WCSI trawl survey. The years represent model years.

Lgth (cm)	Female					Male				
	2013	2015	2017	2019	2021	2013	2015	2017	2019	2021
10	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
11	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
12	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000
13	0.0000	0.0000	0.0002	0.0000	0.0004	0.0000	0.0000	0.0001	0.0000	0.0000
14	0.0002	0.0000	0.0003	0.0001	0.0000	0.0005	0.0001	0.0004	0.0000	0.0000
15	0.0003	0.0002	0.0006	0.0000	0.0027	0.0024	0.0001	0.0008	0.0000	0.0004
16	0.0023	0.0009	0.0014	0.0004	0.0005	0.0010	0.0017	0.0011	0.0012	0.0003
17	0.0011	0.0014	0.0006	0.0008	0.0014	0.0035	0.0039	0.0012	0.0015	0.0009
18	0.0023	0.0002	0.0017	0.0007	0.0045	0.0016	0.0015	0.0025	0.0012	0.0008
19	0.0027	0.0003	0.0016	0.0026	0.0031	0.0016	0.0052	0.0023	0.0022	0.0014
20	0.0036	0.0020	0.0032	0.0026	0.0024	0.0112	0.0155	0.0081	0.0044	0.0098
21	0.0083	0.0079	0.0086	0.0031	0.0107	0.0190	0.0205	0.0138	0.0094	0.0136
22	0.0118	0.0048	0.0156	0.0053	0.0093	0.0370	0.0388	0.0282	0.0152	0.0135
23	0.0216	0.0138	0.0216	0.0135	0.0103	0.0329	0.0301	0.0233	0.0276	0.0157
24	0.0187	0.0143	0.0227	0.0181	0.0181	0.0440	0.0462	0.0374	0.0400	0.0188
25	0.0259	0.0144	0.0213	0.0185	0.0126	0.0502	0.0538	0.0328	0.0471	0.0257
26	0.0243	0.0175	0.0229	0.0236	0.0118	0.0498	0.0334	0.0317	0.0581	0.0244
27	0.0250	0.0214	0.0140	0.0219	0.0115	0.0356	0.0360	0.0294	0.0525	0.0275
28	0.0134	0.0150	0.0191	0.0294	0.0140	0.0266	0.0312	0.0340	0.0651	0.0358
29	0.0169	0.0242	0.0133	0.0264	0.0175	0.0309	0.0352	0.0318	0.0553	0.0407
30	0.0150	0.0198	0.0195	0.0233	0.0234	0.0329	0.0329	0.0330	0.0459	0.0447
31	0.0142	0.0208	0.0165	0.0265	0.0228	0.0251	0.0374	0.0251	0.0320	0.0389
32	0.0088	0.0243	0.0247	0.0272	0.0437	0.0284	0.0366	0.0377	0.0322	0.0382
33	0.0117	0.0205	0.0255	0.0232	0.0416	0.0433	0.0302	0.0288	0.0230	0.0324
34	0.0135	0.0203	0.0176	0.0252	0.0452	0.0311	0.0278	0.0316	0.0189	0.0161
35	0.0179	0.0211	0.0183	0.0209	0.0569	0.0207	0.0226	0.0213	0.0139	0.0179
36	0.0193	0.0199	0.0239	0.0238	0.0470	0.0222	0.0144	0.0134	0.0122	0.0111
37	0.0160	0.0210	0.0264	0.0169	0.0291	0.0124	0.0109	0.0123	0.0072	0.0065
38	0.0244	0.0181	0.0269	0.0170	0.0229	0.0127	0.0114	0.0113	0.0029	0.0040
39	0.0149	0.0164	0.0211	0.0114	0.0317	0.0065	0.0061	0.0090	0.0026	0.0021
40	0.0160	0.0199	0.0187	0.0125	0.0196	0.0066	0.0046	0.0051	0.0041	0.0016
41	0.0160	0.0094	0.0161	0.0075	0.0128	0.0023	0.0037	0.0038	0.0022	0.0007
42	0.0099	0.0125	0.0181	0.0042	0.0103	0.0022	0.0006	0.0019	0.0009	0.0005
43	0.0101	0.0055	0.0154	0.0040	0.0060	0.0006	0.0005	0.0007	0.0007	0.0001
44	0.0068	0.0078	0.0095	0.0039	0.0060	0.0023	0.0000	0.0006	0.0004	0.0000
45	0.0039	0.0028	0.0058	0.0012	0.0028	0.0006	0.0004	0.0000	0.0000	0.0000
46	0.0021	0.0050	0.0044	0.0017	0.0016	0.0000	0.0000	0.0000	0.0001	0.0002
47	0.0008	0.0025	0.0030	0.0011	0.0010	0.0000	0.0000	0.0000	0.0000	0.0000
48	0.0021	0.0011	0.0019	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
49	0.0001	0.0000	0.0014	0.0008	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000
50	0.0000	0.0000	0.0007	0.0001	0.0006	0.0000	0.0000	0.0000	0.0000	0.0000
51	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
52	0.0000	0.0000	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
53	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
54	0.0000	0.0000	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
55	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

APPENDIX 2: MCMC DIAGNOSTICS

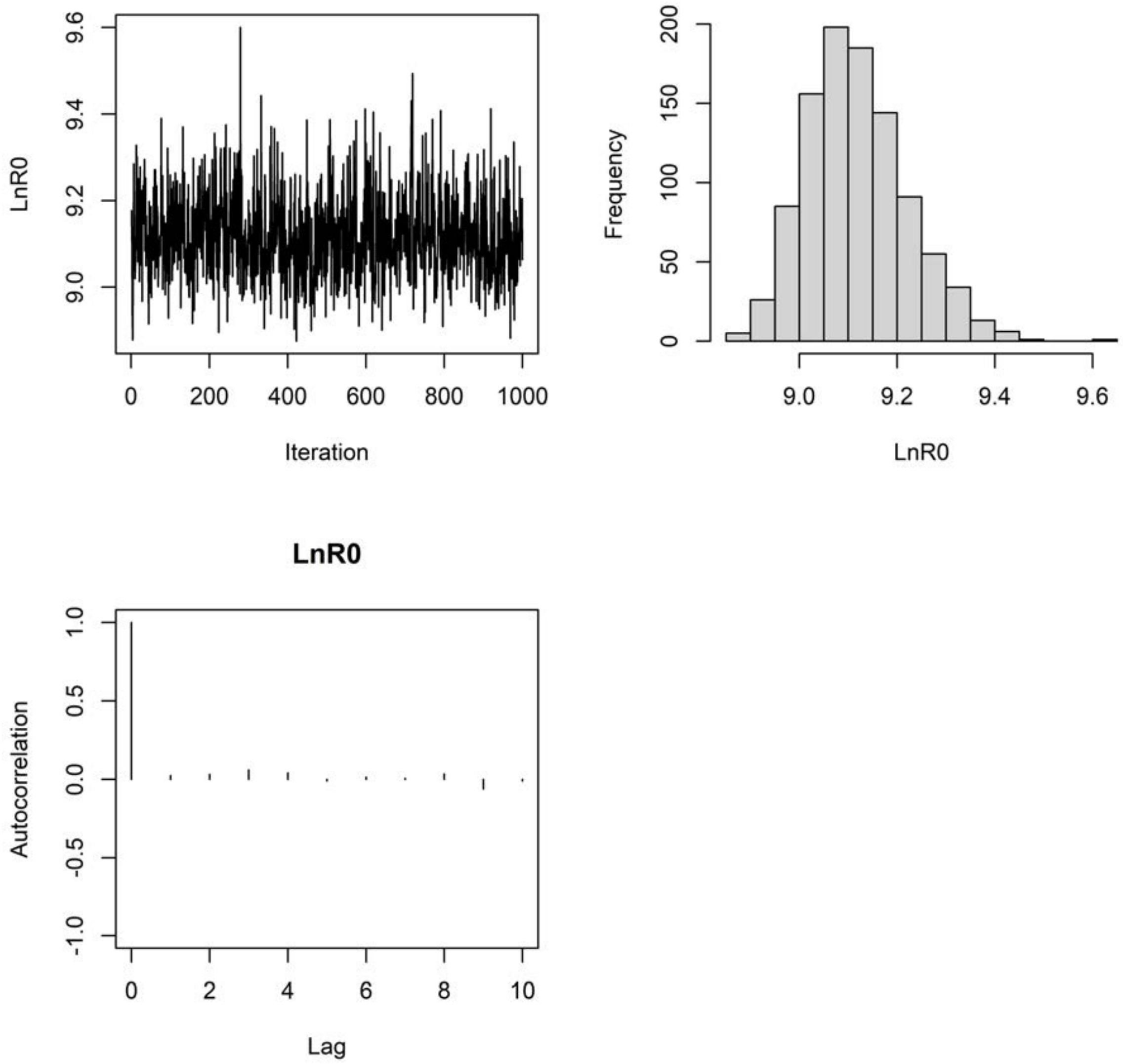

Figure A1: Diagnostics of the MCMC samples of the *LnR0* parameter from the base model.

APPENDIX 3: MANAGEMENT PROCEDURE EVALUATION RESULTS

Table A4: Median values of *SB/SB₀* for the different Management Procedures (MPs) and scenarios evaluated in the simulation testing.

MP	TACC delta	Recruitment	AutoRec	Tsurvey Error	Scalar 0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.5
Base	20%	All	0.30	0%	0.697	0.649	0.610	0.567	0.537	0.504	0.475	0.422
Fslope	20%	All	0.30	0%	0.701	0.652	0.613	0.568	0.537	0.507	0.485	0.435
Fslope2	20%	All	0.30	0%	0.696	0.648	0.609	0.572	0.545	0.510	0.486	0.438
Fslope3	20%	All	0.30	0%	0.720	0.683	0.658	0.628	0.607	0.580	0.567	0.530
Base	20%	Low	0.30	0%	0.418	0.390	0.359	0.334	0.313	0.292	0.277	0.242
Fslope	20%	Low	0.30	0%	0.423	0.391	0.369	0.346	0.329	0.316	0.302	0.282
Fslope2	20%	Low	0.30	0%	0.424	0.398	0.376	0.352	0.337	0.323	0.312	0.289
Fslope3	20%	Low	0.30	0%	0.463	0.444	0.428	0.411	0.395	0.385	0.372	0.352
Base	20%	All	0.50	0%	-	0.669	-	-	0.553	-	0.489	-
Base	20%	All	0.30	10%	-	0.649	-	-	0.532	-	0.476	-
Base	50%	All	0.30	0%	-	0.650	-	-	0.534	-	0.469	-
Base	50%	All	0.30	10%	-	0.650	-	-	0.535	-	0.476	-
Base-LowM	20%	All	0.30	0%	0.598	0.547	0.495	0.459	0.426	0.395	0.370	0.325

Table A5: Median proportion of years with spawning biomass (*SB*) less than 20% SB_0 for the different Management Procedures (MPs) and scenarios evaluated in the simulation testing.

MP	TACC delta	Recruitment	AutoRec	Tsurvey Error	Scalar							
					0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.5
Base	20%	All	0.30	0%	0.000	0.000	0.000	0.010	0.030	0.050	0.080	0.160
Fslope	20%	All	0.30	0%	0.000	0.000	0.000	0.010	0.030	0.050	0.080	0.150
Fslope2	20%	All	0.30	0%	0.000	0.000	0.000	0.010	0.030	0.050	0.080	0.130
Fslope3	20%	All	0.30	0%	0.000	0.000	0.000	0.000	0.010	0.020	0.030	0.060
Base	20%	Low	0.30	0%	0.000	0.030	0.080	0.140	0.200	0.290	0.360	0.530
Fslope	20%	Low	0.30	0%	0.000	0.030	0.070	0.110	0.170	0.220	0.260	0.350
Fslope2	20%	Low	0.30	0%	0.000	0.030	0.060	0.100	0.145	0.200	0.230	0.320
Fslope3	20%	Low	0.30	0%	0.000	0.000	0.030	0.050	0.090	0.110	0.120	0.150
Base	20%	All	0.50	0%	-	0.000	-	-	0.050	-	0.110	-
Base	20%	All	0.30	10%	-	0.000	-	-	0.040	-	0.100	-
Base	50%	All	0.30	0%	-	0.000	-	-	0.000	-	0.040	-
Base	50%	All	0.30	10%	-	0.000	-	-	0.010	-	0.050	-
Base-LowM	20%	All	0.30	0%	0.000	0.000	0.030	0.070	0.110	0.160	0.210	0.320

Table A6: Median proportion of years with spawning biomass (*SB*) less than 10% SB_0 for the different Management Procedures (MPs) and scenarios evaluated in the simulation testing.

MP	TACC delta	Recruitment	AutoRec	Tsurvey Error	Scalar 0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.5
Base	20%	All	0.30	0%	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fslope	20%	All	0.30	0%	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fslope2	20%	All	0.30	0%	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fslope3	20%	All	0.30	0%	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Base	20%	Low	0.30	0%	0.000	0.000	0.000	0.000	0.000	0.010	0.020	0.080
Fslope	20%	Low	0.30	0%	0.000	0.000	0.000	0.000	0.000	0.010	0.020	0.040
Fslope2	20%	Low	0.30	0%	0.000	0.000	0.000	0.000	0.000	0.010	0.020	0.040
Fslope3	20%	Low	0.30	0%	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.010
Base	20%	All	0.50	0%	-	0.000	-	-	0.000	-	0.000	-
Base	20%	All	0.30	10%	-	0.000	-	-	0.000	-	0.000	-
Base	50%	All	0.30	0%	-	0.000	-	-	0.000	-	0.000	-
Base	50%	All	0.30	10%	-	0.000	-	-	0.000	-	0.000	-
Base-LowM	20%	All	0.30	0%	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.030

Table A7: Median annual catch (t) for the different Management Procedures (MPs) and scenarios evaluated in the simulation testing.

MP	TACC delta	Recruitment	AutoRec	Tsurvey Error	Scalar							
					0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.5
Base	20%	All	0.30	0%	607	701	785	851	903	946	982	1034
Fslope	20%	All	0.30	0%	607	704	781	845	898	937	970	1017
Fslope2	20%	All	0.30	0%	602	702	778	844	891	927	963	1007
Fslope3	20%	All	0.30	0%	545	628	687	731	784	812	840	896
Base	20%	Low	0.30	0%	388	445	492	530	562	584	599	625
Fslope	20%	Low	0.30	0%	384	436	480	509	532	549	561	589
Fslope2	20%	Low	0.30	0%	376	429	471	500	516	535	552	573
Fslope3	20%	Low	0.30	0%	288	330	364	393	416	436	452	484
Base	20%	All	0.50	0%	-	711	-	-	916	-	988	-
Base	20%	All	0.30	10%	-	704	-	-	894	-	967	-
Base	50%	All	0.30	0%	-	708	-	-	927	-	1006	-
Base	50%	All	0.30	10%	-	703	-	-	921	-	1001	-
					-							
Base-LowM	20%	All	0.30	0%	647	738	802	850	886	904	924	950

Table A8: Standard deviation of annual catches (t) for the different Management Procedures (MP) and scenarios evaluated in the simulation testing.

MP	TACC delta	Recruitment	AutoRec	Tsurvey Error	Scalar							
					0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.5
Base	20%	All	0.30	0%	195	229	253	277	297	315	336	369
Fslope	20%	All	0.30	0%	194	226	252	279	301	317	340	383
Fslope2	20%	All	0.30	0%	195	233	255	281	305	323	347	385
Fslope3	20%	All	0.30	0%	220	259	283	307	328	346	356	380
Base	20%	Low	0.30	0%	190	220	246	255	268	285	295	304
Fslope	20%	Low	0.30	0%	194	229	252	268	285	300	312	322
Fslope2	20%	Low	0.30	0%	197	232	256	272	289	304	314	323
Fslope3	20%	Low	0.30	0%	220	253	281	290	304	316	325	328
Base	20%	All	0.50	0%	-	242	-	-	326	-	359	-
Base	20%	All	0.30	10%	-	233	-	-	304	-	335	-
Base	50%	All	0.30	0%	-	262	-	-	362	-	410	-
Base	50%	All	0.30	10%	-	285	-	-	383	-	431	-
Base-LowM	20%	All	0.30	0%	201	235	260	282	305	322	333	361