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Tini a Tangaroa

The 2022 stock assessment of hake (*Merluccius australis*) off the west coast South Island (HAK 7)

New Zealand Fisheries Assessment Report 2023/48

A. Dunn,
S. Mormede,
D.N. Webber

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EXECUTIVE SUMMARY

Dunn, A.[1]; Mormede, S.[2]; Webber, D.N.[3] (2023). The 2022 stock assessment of hake (*Merluccius australis*) off the west coast South Island (HAK 7).

***New Zealand Fisheries Assessment Report 2023/48*. 45 p.**

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 and caught mainly by deepwater demersal trawls. Hake are managed in three Fishstocks: (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). Hake are assessed as three main biological stocks: the west coast South Island, Chatham Rise, and Sub-Antarctic.

This report provides a stock assessment of the west coast South Island stock (hake in HAK 7 off the west coast of New Zealand) up to the end of the 2021–22 fishing year. The indices of abundance provided to the model were the west coast South Island *Tangaroa* trawl survey series, along with fishery and survey age frequency data. This assessment updated the previous model with new observations made since the last assessment, small revisions to the annual cycle, and revised the selection of strata used in the time series of the biomass indices. These changes and the new observations suggested that while current status had significantly improved, the low point estimated in the previous assessment in 2016 was still estimated to be low.

The median of the posterior distribution of initial biomass was 78 870 t (95% credible intervals 74 140–84 810) with current status of 39% B_0 (95% credible intervals 30–52% B_0). Markov chain Monte Carlo (MCMC) iterations did not indicate any evidence of non-convergence and diagnostics of the model fits were reasonable.

MCMCs were carried out for the base case and the sensitivities. Assessment model sensitivities did not suggest that alternative assumptions would lead to a significantly different estimate of current status, but the model was highly sensitive to assumptions of recent and future year class strengths. MCMC diagnostics were reasonable for most estimated parameters. Model projections suggested that the biomass of hake off the west coast South Island would increase under the assumptions of average recruitment and current catch levels, but would remain flat over the next five years if future recruitment was low and catches were at the level of the total allowable commercial catch.

[1] Ocean Environmental Ltd., Wellington, New Zealand.
[2] SoFish Consulting Ltd., Wellington New Zealand.
[3] Quantifish Ltd., Tauranga, New Zealand.

1. INTRODUCTION

Hake (*Merluccius australis*, HAK) 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. 2023).

The current management of hake divides the fishery into three Fishstocks (see 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). 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 southern part of the northern regions in HAK 1), and the Sub-Antarctic (HAK 1).

Previous analyses showed that the length frequencies of hake were different between the west coast and both the Chatham Rise and the Sub-Antarctic. The growth parameters were also different between the three areas (Horn 1997) and juvenile hake have been found in all three areas (Hurst et al. 2000). Analysis of morphometric data from the 1990s (Colman, NIWA, unpublished data) showed little difference between hake on the Chatham Rise and those off the east coast of the North Island, but significant differences between Chatham Rise hake and those from the Sub-Antarctic, Puysegur, and off the west coast of the South Island. Hake from Puysegur were like those from off the west coast South Island and may be different from the Sub-Antarctic hake. Hence, the stock affinity of hake from Puysegur was considered to be uncertain (Kienzle et al. 2019).

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. 2021a).

Previous west coast South Island hake stock assessments were implemented as single sex and area integrated statistical catch-at-age models using commercial catch-at-age frequency, catch per unit effort (CPUE), resource survey biomass, and survey age frequency observations (Kienzle et al. 2019). The Bayesian stock assessment software CASAL (Bull et al. 2012) has been used for all hake assessments since 2002–03, and the previous most recent hake assessments were Holmes (2021) for the Chatham Rise, Dunn et al. (2021a) for the Sub-Antarctic, and Kienzle et al. (2019) for the west coast South Island. The most recent characterisation of the fishery and CPUE indices were updated by Dunn et al. (2023) including data up to the end of the 2020–21 fishing year.

The previous west coast South Island hake stock assessment concluded that the spawning stock in 2019 had been reduced to less than 20% of the pre-exploitation biomass (B_0), well below the management target of 40% B_0. The assessment found that the predicted status of the stock in future years, with catch the same as recent levels (3000 t) and with average future recruitment, would be at about the same level. Increases in catches or continued lower than average recruitment would cause further stock decline. However, previous analyses for west coast South Island hake (reported in the 2021 plenary, Fisheries New Zealand 2023) noted a number of major sources of uncertainty in the assessment, including uncertainty about the size of recent year classes effects, the reliability of stock projections, and the adequateness of the spatial and temporal representativeness of the deepwater survey for hake off the west coast South Island.

Biomass indices for west coast South Island offshore trawl surveys are available from 2000 to 2021, but there were no offshore surveys from 2001 to 2011. While survey biomass indices had suggested a sharp decline in 2016 and 2018, the most recent survey biomass in 2021 had increased to a level near the 2012 estimate. In addition, the highly skewed sex ratio and the low catch rate in the 2016 survey suggest that the survey may have underestimated biomass in that year. CPUE indices have been investigated (e.g., Ballara 2018, Horn & Ballara 2018, Finucci 2019, Dunn et al. 2023) but were contradictory to the trend observed in the trawl survey indices. Fishery operational characteristics of the fleet, and in particular its interaction while targeting hoki (the predominant target species off the west coast South Island) are likely causes of any patterns in CPUE, and hence they were rejected as indices of hake abundance.

This report fulfils Specific Objective 2 of Project HAK2021-01. The overall Objective was "To carry out stock assessments of hake (*Merluccius australis*) off the west coast of the South Island (HAK 7) including estimating stock biomass and stock status" and Specific Objective 2 was "To update the stock assessment of the west coast South Island hake stock including estimates of current biomass, the status of the stock in relation to management reference points, and future projections of stock status as required to support management.". This report updates the west coast South Island stock assessment with the most recent available data up to the end of the 2020–21 (2021) fishing year. The catch history, resource survey indices, and CPUE indices are described by Dunn et al. (2023), and the age frequency data are described by Saunders et al. (2021).

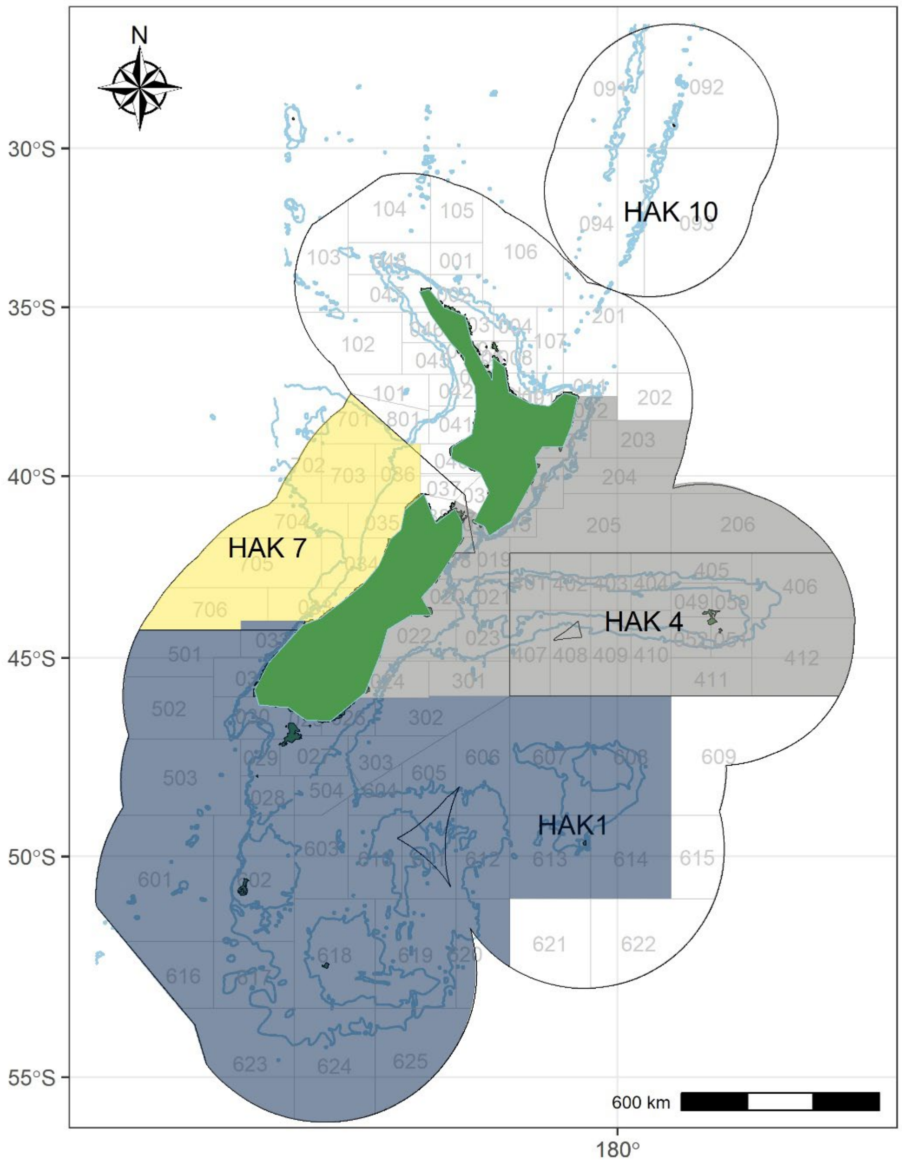

Figure 1: Quota Management Areas (QMAs) HAK 1, 4, 7, and 10 (black lines), statistical areas (grey), and hake biological stock boundaries: west coast South Island (yellow), Chatham Rise (light grey), and Sub-Antarctic (dark grey).

2. METHODS

2.1 Data available for the assessment

2.1.1 Catch history

The reported catch history of hake in each of the Quota Management Area (QMA) is given in Table 1. In HAK 7, reported landings peaked at almost 10 000 t in 1995–96 and have since declined to about 1400 t in the most recent year. The Total Allowable Commercial Catch (TACC) for hake was 7700 t until 2016–17 and was then reduced in two steps to 5064 t in 2017–18 and to 2272 t in 2019–20.

In the late 1990s and early 2000, hake fishers misreported hake catches between QMAs, typically misreporting catches of hake from HAK 7 as catch from either HAK 1 or HAK 4. The reported catches of hake in each area were reviewed in 2002 and several suspect records identified. Dunn (2003b) provided revised estimates of the total landings by stock. Almost all the area misreporting was from

HAK 7 (west coast South Island) to the Chatham Rise (HAK 4 and the part of HAK 1 on the Chatham Rise), with a small amount in the Sub-Antarctic area of HAK 1 (Dunn 2003b). Dunn (2003b) estimated that the level of hake over-reporting on the Chatham Rise (and hence under-reporting off the west coast South Island) was between 16 and 23% (700–1000 t annually) of landings between 1994–95 and 2000–01, mainly in June, July, and September. Probable levels of area misreporting prior to 1994–95 and between the west coast South Island and Sub-Antarctic were estimated as low (Dunn 2003b). There has been no evidence of similar area misreporting since 2001–02 (Ballara 2018). A revised catch history for hake, accounting for this misreporting, for each stock is given in Table 1 and Figure 2. Catches were mostly taken in the winter months (June to September, see Figure 3). The total catch for the 2021–22 fishing year was not known at the time of the analysis for this report and was assumed to be equal to the average catch reported over the most recent three years.

Table 1: Total (scaled) catches (t) by stock for hake from 1990 to 2021 and assumed catch for WCSI for 2022, for (left columns) the fishing year (where 1990 is 1 October 1989–30 September 1990). 'Not assigned' includes catches from areas that had no fishing location or statistical area or were north of the boundaries used for the stock definitions.

Fishing year	Chatham Rise	Sub-Antarctic	WCSI	Not assigned	Total
1990	1 015	1 827	4 903	39	7 784
1991	963	2 366	6 147	73	9 549
1992	2 420	2 749	3 026	1	8 196
1993	2 801	3 265	7 121	37	13 225
1994	2 952	1 452	2 958	2	7 364
1995	4 097	1 844	8 839	9	14 789
1996	4 535	2 888	8 662	46	16 131
1997	4 790	2 274	6 111	48	13 222
1998	4 691	2 601	7 404	59	14 755
1999	4 381	2 792	8 159	6	15 338
2000	3 691	3 011	6 895	2	13 600
2001	2 965	2 787	8 357	7	14 117
2002	1 785	2 510	7 519	0	11 813
2003	1 407	2 741	7 432	1	11 581
2004	2 492	3 251	7 943	0	13 686
2005	3 532	2 530	7 314	0	13 377
2006	494	2 555	6 905	0	9 955
2007	1 112	1 812	7 668	2	10 594
2008	1 109	2 204	2 617	0	5 930
2009	1 845	2 427	5 953	1	10 226
2010	412	1 958	2 346	0	4 716
2011	975	1 288	3 574	1	5 838
2012	216	1 893	4 459	0	6 568
2013	373	1 883	5 434	1	7 690
2014	219	1 832	3 641	0	5 693
2015	390	1 639	6 219	0	8 248
2016	355	1 504	2 863	1	4 722
2017	406	1 037	4 701	1	6 145
2018	412	1 205	3 085	1	4 704
2019	443	636	1 562	0	2 642
2020	266	930	2 062	4	3 262
2021	355	1 355	1 367	0	3 077
2022	–	–	1 664	–	–

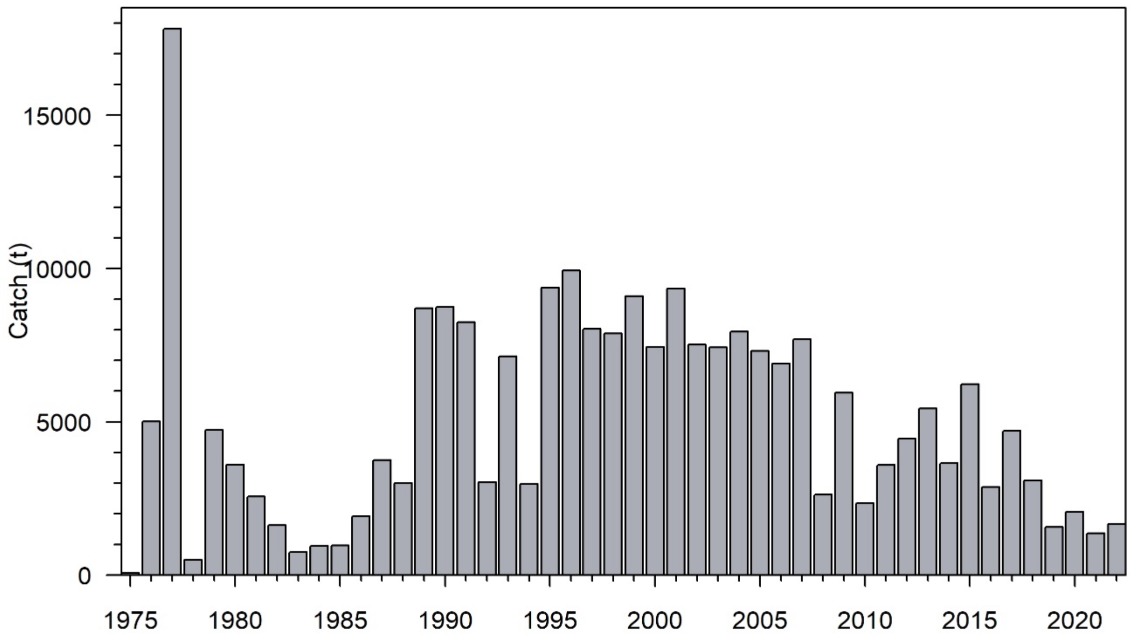

Figure 2: Annual reported catch of west coast South Island hake for the fishing years 1974–75 to 2021–22.

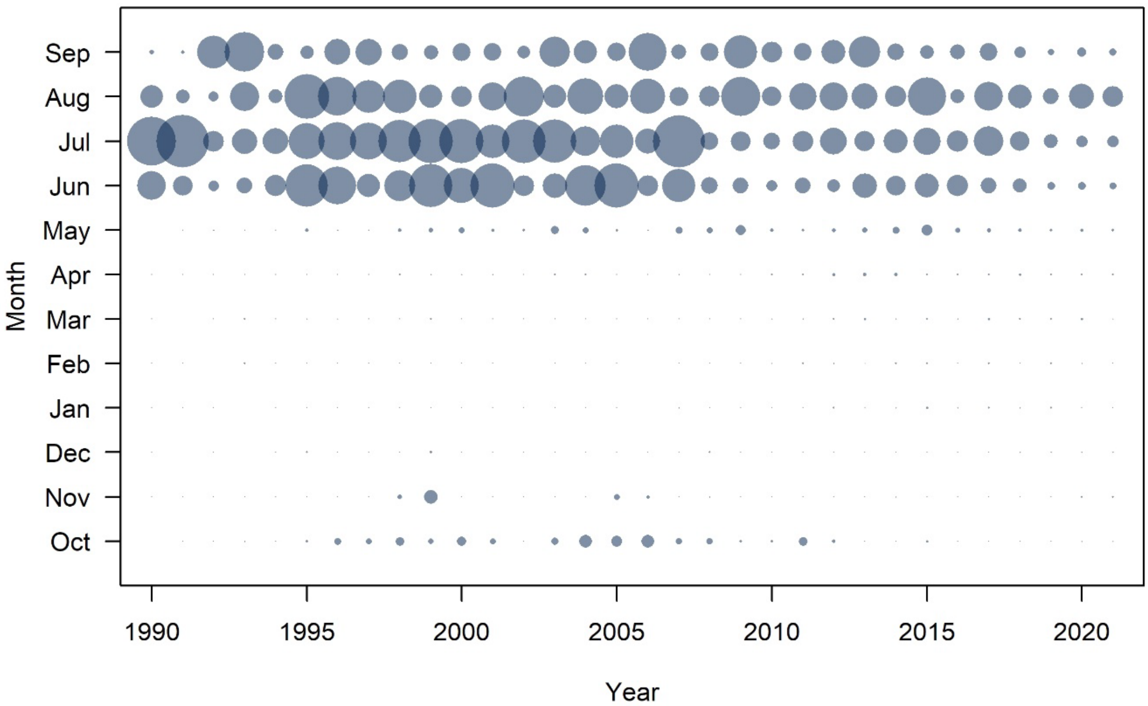

Figure 3: Relative catch of hake off the west coast South Island by month and calendar year, 1990–2021.

2.1.2 Biological parameters

Revised length-weight and growth curve parameters were described by Dunn et al. (2023), using all available data. Revised length-weight parameters and Bayesian von Bertalanffy growth curves are given in Table 2. However, the differences between these and the parameters for the length weight (Horn 2013a) and growth estimates (Horn 2008, 2013a) previously used were relatively small.

Parameters for natural mortality were given by Horn & Francis (2010), based on estimates derived from age data using methods of Chapman & Robson (1960), Ricker (1975), and Hoenig (1983). The stock recruitment relationship was assumed, based on values used for previous assessments (Dunn 2019) and ageing error from the values given by Horn & Francis (2010). Males and females were assumed to be 50:50 at recruitment to the model (i.e., at age 1) and all mature fish were assumed to spawn in each year (Table 2). Maturity values were from (Horn 2008) (see Table 3).

Table 2: Biological parameters for west coast South Island hake.

Relationship	Reference	Parameter (units)	Both	Male	Value Female
Natural mortality*	(Horn & Francis 2010)	M (y^{-1})		0.19	0.19
von Bertalanffy growth	(Dunn et al. 2021b)	t_0 (y)		83.1	107.0
		k (y^{-1})		0.329	0.192
		L_∞ (cm)		-0.43	-0.98
		CV		0.07	0.10
Length-weight	(Dunn et al. 2021b)	a (g cm^{-1})		3.34e-06	3.48e-06
		b		3.175	3.177
Beverton-Holt stock recruitment relationship					
Stock recruitment steepness	(Horn & Francis 2010)	h	0.8		
Recruitment variability		σ_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		U_{max}	0.7		

* Assumed value, but also estimated in a sensitivity model.

Table 3: Maturity-at-age for west coast South Island hake (Horn 2008).

Age (y)	1	2	3	4	5	6	7	8	9	10+
Male	0.00	0.01	0.05	0.27	0.22	0.73	0.95	0.99	1.00	1.00
Female	0.00	0.02	0.07	0.25	0.57	0.84	0.96	0.99	1.00	1.00

2.1.3 Observations

Observational data for the west coast South Island hake stock assessment included the biomass indices from the series of west coast South Island offshore trawl surveys from RV *Tangaroa*. Survey biomass indices are available from 2000 to 2021 (Devine et al. 2022), but there were no surveys from 2001 to 2011. The core strata for the survey had been consistently surveyed since 2000, but additional strata (both shallower and deeper) were added in 2012 and in 2016 (Figure 4). The pattern in the surveys using the additional strata were similar to the core strata, and the assessment used the *Tangaroa* series based on core strata.

The trawl survey series biomass indices and associated coefficients of variation (CVs) are given in Table 4 (see also appendix A of Dunn et al. 2023). While survey biomass indices had suggested a sharp decline in 2016 and 2018, the most recent survey in 2021 had increased to a level near the 2012 estimate. In addition, the highly skewed sex ratio (Figure 5) and the low catch rate in the 2016 survey suggest that the survey may have underestimated biomass in that year. An additional biomass index from the *Kaharoa* surveys of the inshore west coast South Island was not included in the base case assessment because it only catches juveniles, and the representativeness of the series was unlikely to index the population.

Lognormal errors, with known CVs, were assumed for all relative biomass observations. The CVs available for those observations of relative abundance allow for sampling error only. Additional variance, assumed to arise from differences between model simplifications and real-world variation, was added to the sampling variance. The additional variance, termed process error, was estimated in the models at maximum posterior density (MPD) level only because mixing of these process error parameters is generally poor when using the Metropolis-Hastings MCMC algorithm. Multinomial errors were assumed for the age composition observations. The effective sample sizes for the composition samples were estimated following method TA1.8 as described by Francis (2011). Initial and effective sample sizes for the survey proportions-at-age are given in Table 5.

The commercial catch-at-age frequencies were assumed to be observations of the removals from each of three spatially defined fisheries, defined as the areas used by Horn (2011); ‘south shallow’, south of 42.55° S and shallower than 629 m depth; ‘north shallow’, north of 42.55° S and shallower than 629 m depth; and ‘deep’, all other areas deeper than 629 m (Figure 6).

Age frequency observations for the trawl survey series were available for each of the surveys (Figure 7) and were included as sexed proportions-at-age. Commercial catch-at-age frequencies (Saunders et al. 2021, Ballara et al. 2022) were available for most years (Table 5 and Figure 7) and were also included as sexed proportions-at-age. As the proportions of fish less than five years old were not considered reliable observations of the juvenile population (see Dunn et al. 2023), fish of ages less than five were excluded from the observations of both the commercial catch-at-age and survey age frequencies. Preliminary models that used the observations from the survey biomass split into juveniles and adults, and the age frequencies into juveniles and adults (i.e., by considering juveniles as males < 65 cm and females < 69 cm), were also developed. Investigations using these models provided little information on year class strength (YCS) and were not further developed for the final assessment (see discussion below). Survey observations were assumed to be observations of the vulnerable population.

The multinomial sample size (*N*) for the proportions-at-age observations were generated using a two-step process. First, the sample sizes were derived by assuming the relationship between the observed proportions, E_i, and estimated CVs, c_i, followed that for a multinomial distribution with unknown sample size N_j. The estimated sample size was then derived using a robust non-linear least squares fit of $\log(c_i) \sim \log(P_i)$ (labelled the initial sample size). Second, estimates of the effective sample size, N_j', were made from iterative model fitting following method TA1.8 as described in appendix A of Francis (2011). Initial and effective sample sizes for commercial catch-at-age data are given in Table 5.

Ageing error was accounted for by modifying the likelihoods for the proportions-at-age data such that *E*i was replaced by *E*’i, where *E*’i were the expected proportions-at-age 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).

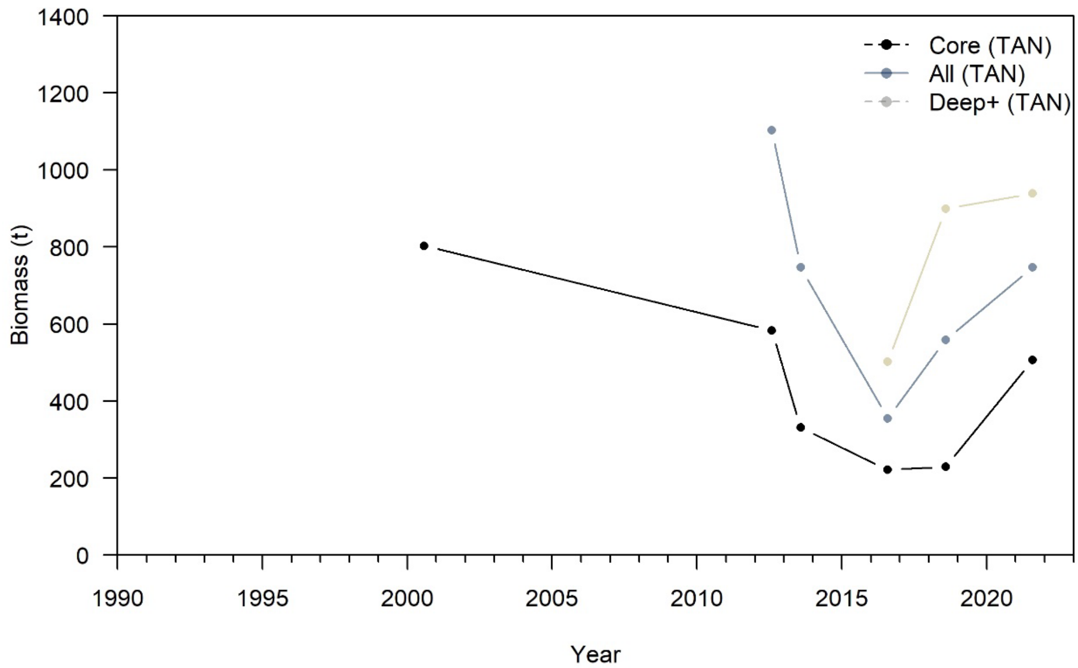

Figure 4: Biomass indices for the *Tangaroa* core, deep, and deep+ strata for hake off the west coast South Island, 2000–2022.

Table 4: Research survey indices (and associated CVs) for *Kaharoa* inshore and deepwater *Tangaroa* core strata for hake off the west coast South Island. Note the *Kaharoa* series was not used in the base case model for the stock assessment.

Model	*Kaharoa*			*Tangaroa*		
year	Biomass (t)	CV	Reference	Biomass (t)	CV	Reference
1992	390	0.25	(MacGibbon 2019)			
1994	99	0.31	(MacGibbon 2019)			
1995	5 197	0.27	(MacGibbon 2019)			
1997	1 019	0.46	(MacGibbon 2019)			
2000	15	0.36	(MacGibbon 2019)	803.0	0.13	(O'Driscoll & Ballara 2018)
2003	55	0.47	(MacGibbon 2019)			
2005	1 673	0.30	(MacGibbon 2019)			
2007	359	0.35	(MacGibbon 2019)			
2009	212	0.56	(MacGibbon 2019)			
2011	44	0.36	(MacGibbon 2019)			
2012				582.8	0.13	(O'Driscoll & Ballara 2018)
2013	36	0.41	(MacGibbon 2019)	330.9	0.17	(O'Driscoll & Ballara 2018)
2015	81	0.37	(MacGibbon 2019)			
2016				221.5	0.24	(O'Driscoll & Ballara 2018)
2017	217	0.61	(MacGibbon 2019)			
2018				229.2	0.33	(O'Driscoll & Ballara 2019)
2019	111	0.33	(MacGibbon 2019)			
2021	179	0.63	(MacGibbon et al. 2022)	506.6	0.34	(Devine et al. 2022)

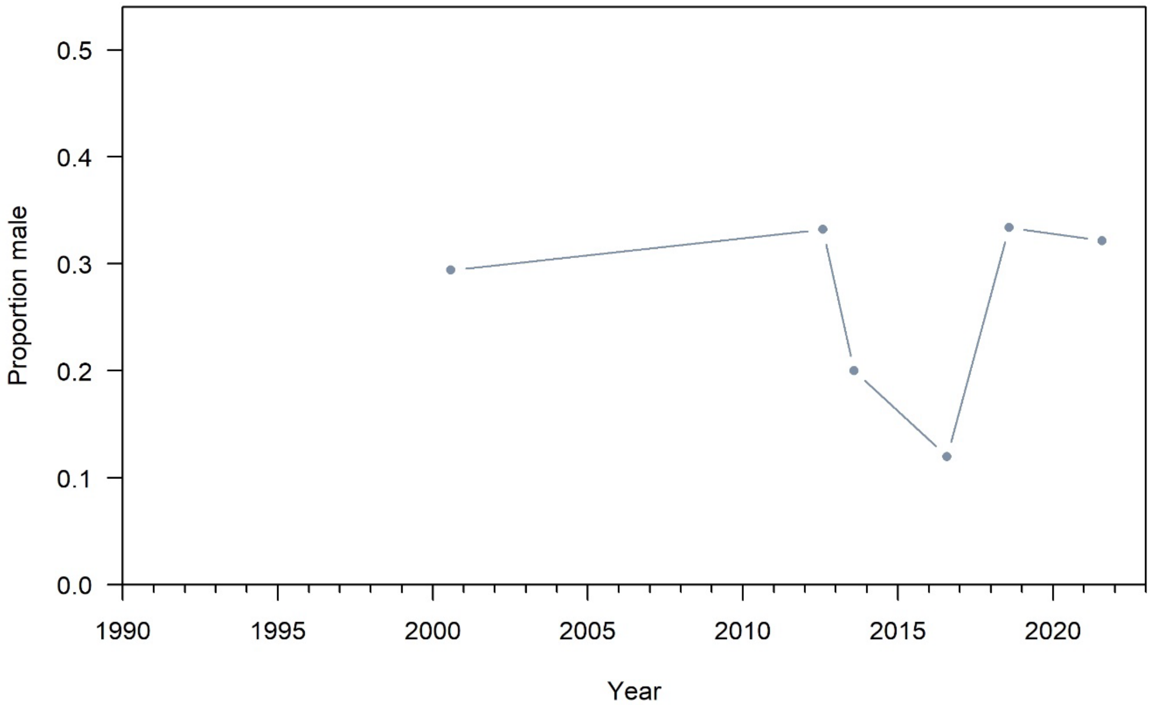

Figure 5: Proportions of males in biomass indices for the *Tangaroa* core strata for hake off the west coast South Island, 2000–2022.

Table 5: Catch-at-age data for the west coast South Island stock, giving the multinomial initial and effective sample sizes assumed for each sample for the *Tangaroa* trawl survey, and the commercial catch-at-age data for the deep, north shallow, and south shallow strata, 1990–2021. (Source: Saunders et al. 2021, Ballara et al. 2022.)

Model year	*Tangaroa* trawl survey		Fishery catch-at-age Deep		North shallow		South shallow	
	Initial	Effective	Initial	Effective	Initial	Effective	Initial	Effective
1990			213	19.3	211	25.2	124	9.5
1991			442	40.0	246	29.4	146	11.2
1992			227	20.6	203	24.3	191	14.6
1993			169	15.3	157	18.8	43	3.3
1997			194	17.6	286	34.2	202	15.5
1998			156	14.1	295	35.3	239	18.3
1999			487	44.1	528	63.1	306	23.5
2000	289	70.3	239	21.6	399	47.7	290	22.2
2001			202	18.3	346	41.4	201	15.4
2002			224	20.3	274	32.8	304	23.3
2003			206	18.7	383	45.8	259	19.9
2004			264	23.9	407	48.7	329	25.2
2005			122	11.1	171	20.4	241	18.5
2006			402	36.4	249	29.8	344	26.4
2007			471	42.6	128	15.3	173	13.3
2008			473	42.8	349	41.7	80	6.1
2009			383	34.7	332	39.7	124	9.5
2010			67	6.1	198	23.7	25	1.9
2011			511	46.3	366	43.8	169	13.0
2012	249	60.5	473	42.8	578	69.1	115	8.8
2013	143	34.8	592	53.6	601	71.8	291	22.3
2014			675	61.1	606	72.4	233	17.9
2015			824	74.6	593	70.9	232	17.8
2016	47	11.4	537	48.6	637	76.2	268	20.5
2017			635	57.5	720	86.1	206	15.8
2018	46	11.2	579	52.4	608	72.7	265	20.3
2019			132	12.0	371	44.4	218	16.7
2020			278	25.2	299	35.7	118	9.0
2021	104	25.3	247	22.4	392	46.9	143	11.0

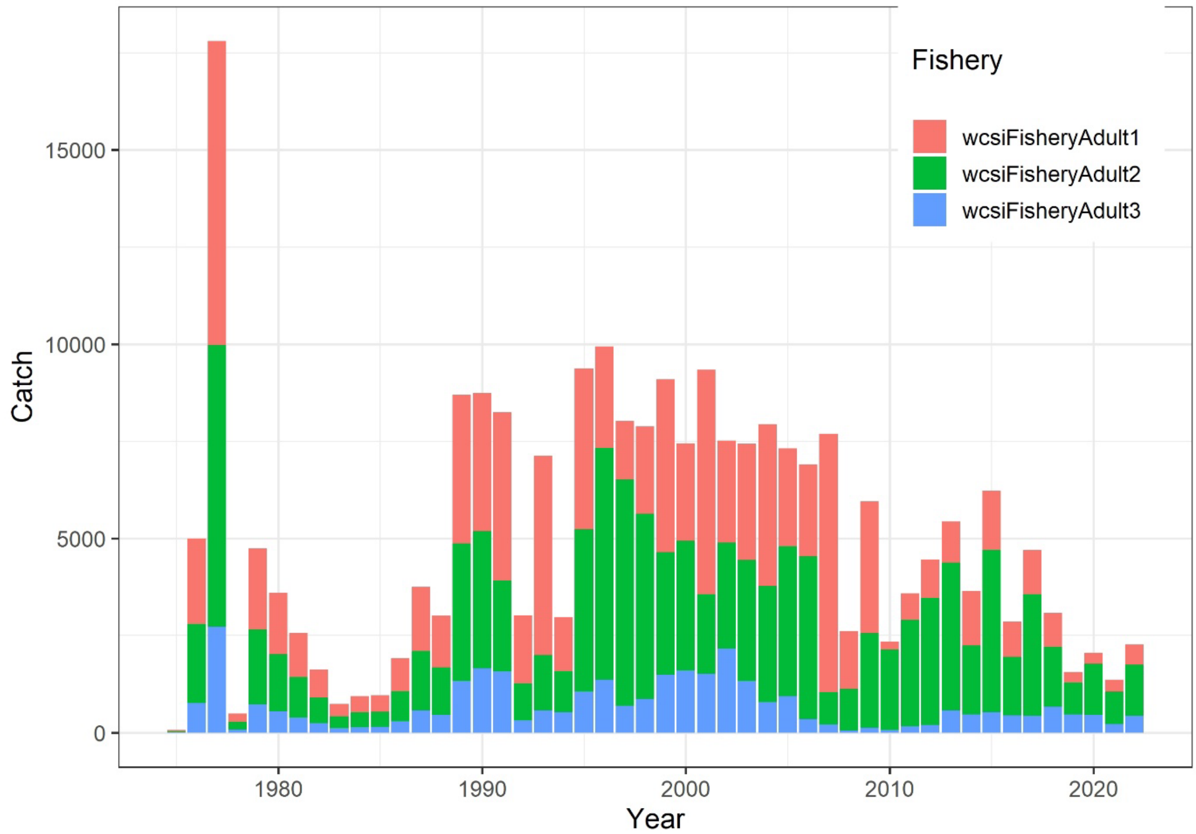

Figure 6: Catch history (t) for hake in the deep (wcsiFisheryAdult1), north shallow (wcsiFisheryAdult2), and south shallow (wcsiFisheryAdult3) fisheries off the west coast South Island, 1974–2022 fishing years.

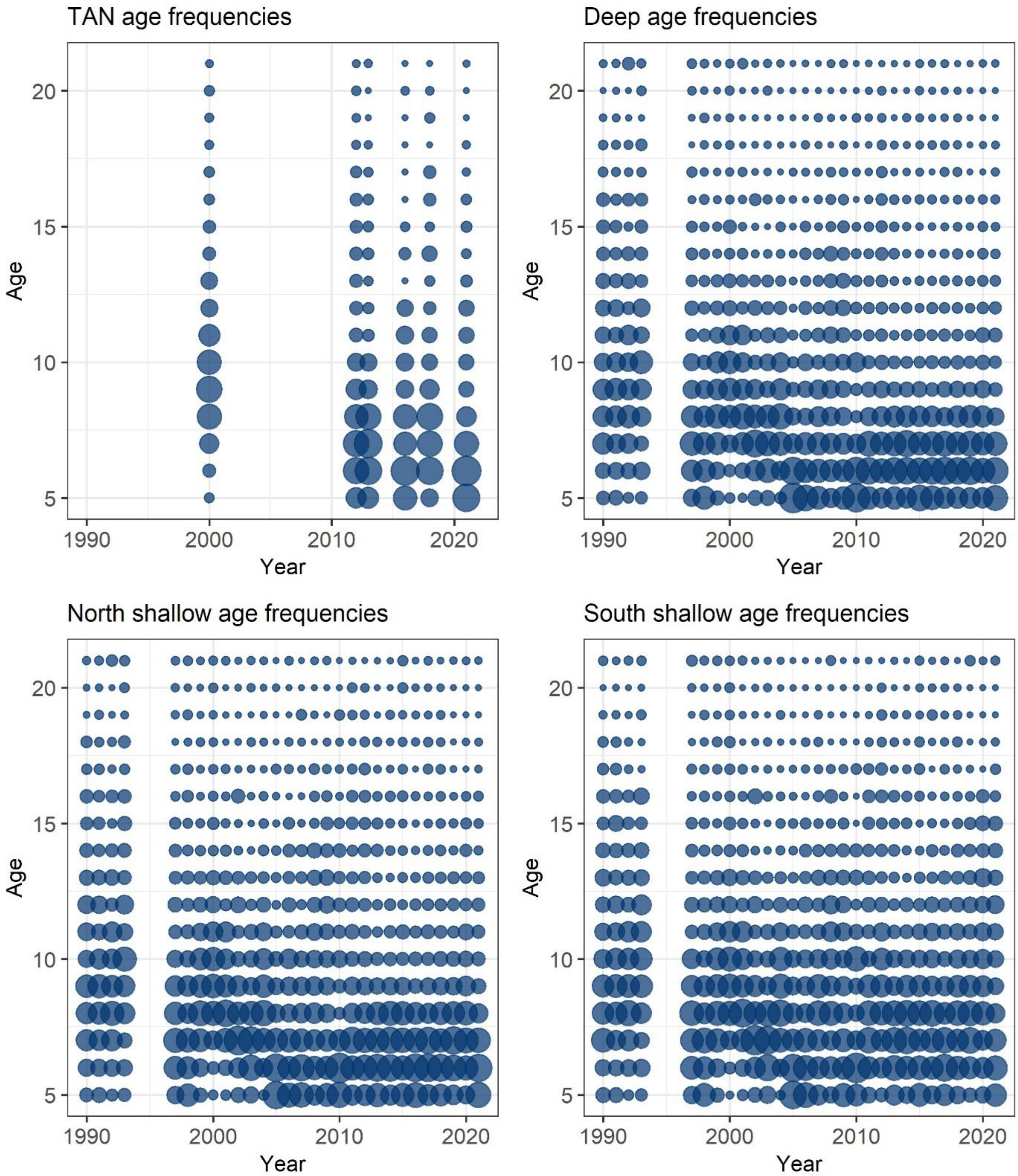

Figure 7: Relative proportions-at-age observations for the (top left) *Tangaroa* trawl survey series and the commercial catch-at-age data for the deep (wcsiFisheryAdult1)), north shallow (wcsiFisheryAdult2), and south shallow (wcsiFisheryAdult3) strata, for years 1990–2021. (Source: Saunders et al. 2021, Ballara et al. 2022.)

2.2 Model structure

Stock assessments have been carried out since 1991–92 (Colman et al. 1991) and have used an integrated assessment model implemented in CASAL since 2000–01 (Dunn 2001).

The primary source of abundance information is the west coast South Island trawl survey, with the core strata forming a consistent time series since 2000 (see Table 4 above). The most recent previous assessment was in 2019 (Kienzle et al. 2019). The model was structured as a sex- (male and female) and age-structured model with ages from 1 to 30, whereby the number of male and female 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). The population was initialised assuming an unfished equilibrium age structure at an initial biomass (i.e., with constant recruitment). The initial biomass was estimated by the model. The model was run from the 1975 to 2022 fishing years, and the annual cycle was broken into three discrete time steps: summer (October–May, time step one), winter (June–September, time step two), and then an age incrementation step (time step three). The annual cycle assumed in the model is described in Table 6.

Initially, in the first time step, the age of all fish was incremented by one year, with fish in the plus group remaining in that group. Biomass calculations at any point in the model were made by multiplying the number of fish in each year class by the size-at-age relationship and the length-weight relationship for each sex separately.

Recruitment was assumed to occur at the beginning of the first 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 frequency data were not available (see later). Future recruitment was assumed to be lognormally distributed with variability observed in the estimated historical recruitment for each Markov chain Monte Carlo (MCMC) iteration (see below).

The catch history for the fishery was assumed as all occurring in second time step (winter) based on the relative reported catches in each month; about 99% of the catch occurred from June to September. For the years before 1991, when catch by month information was not available, the catch was assumed to be in winter. Fishing mortality for each fishery was applied by removing half of the natural mortality for the time step, then mortality from the fishery, then the remaining half of the natural mortality for the time step.

The fishing selectivity parameters were estimated by the model through fitting of the observations, particularly the fisheries age frequency data. The maturation process was applied at the beginning of the winter time step. Maturation was specified as the time-invariant proportion of male and female fish-at-age that was mature and calculated as at the middle of the winter time step.

Model parameters were estimated by minimising the total objective function, which was the sum of the negative log-likelihoods from the data, the negative-log priors, and the penalty functions used to apply model constraints. Penalties were applied to catch data if the biomass from the model was too small to allow the catch to be taken, but this did not enter the model in any of the scenarios modelled. A small penalty was applied to the estimates of year class strength to encourage estimates that averaged one. Initial fits were evaluated at the maximum of the posterior distribution (MPD) and data weightings determined by considering MPD fits and residual patterns and qualitative evaluation of MPD profile distributions (i.e., by evaluating the minimum objective function while fixing one parameter and allowing all other parameters to vary).

The initial spawning stock biomass (B_0) was estimated in the model, as were year class strengths and selectivity ogives. The *Tangaroa* survey selectivity ogives were fitted as a logistic curve, whereas the *Kaharoa* survey selectivity ogives were fitted as a double normal curve. The fishery catch and age composition data were included using an 'areas-as-fleets' approach, using the deep (wcsiFisheryAdult1), north shallow (wcsiFisheryAdult2), and south shallow (wcsiFisheryAdult3) strata. Fishery selectivity ogives were fitted as logistic curves because double normal assumptions typically estimated a curve that was very close to a logistic shape. Selectivities were assumed to be constant for all years in each fishery or survey. The estimated parameters, their shape, prior assumptions, and bounds are summarised in Table 7.

Most priors were intended to be relatively uninformed and were specified with wide bounds. The exceptions were the choice of informative priors for the trawl survey catchability q. The prior for natural mortality (M) was assumed to be normally distributed, with mean 0.19 y^{-1} and standard deviation 0.05, based on previous stock assessments. However, a sensitivity with mean 0.19 y^{-1} and standard deviation of 0.2 was also investigated.

As with previous assessments for the west coast South Island, the prior for the *Tangaroa* survey q was assumed to be informative and was assumed equal to the prior calculated by Kienzle et al. (2019). Here, the Sub-Antarctic hake survey prior was assumed as having an equivalent catchability but adjusted for the relative areas of the Chatham Rise and west coast South Island surveys. The west coast South Island survey area in the 200–800 m depth range comprised 54% of the entire west coast South Island (excluding the Challenger Plateau), i.e., 12 928 km^2 out of 24 000 km^2. The mean of the Chatham Rise prior (Holmes 2021) was modified by this proportion and the lower bound was reduced to 0.01.

Bayesian inference was used to obtain samples from the posterior distribution of model parameters using the Metropolis-Hastings algorithm (Gelman et al. 1995; Gilks et al. 1998). MCMCs were initialised using a random starting point near the MPD (generated from a multivariate normal distribution, centred on the MPD, with covariance equal to the inverse Hessian matrix), with a correlation matrix derived from the inverse Hessian. MCMCs were specified to have burn-in length of 2.5×10^6 iterations, with every 2500th sample taken from the next 5×10^6 iterations (i.e., a final sample of length 1000 was taken after the burn-in to sample from the posterior distribution). Chains were investigated for evidence of non-convergence using multiple-chain comparisons (for a total of three chains in the base case model), standard diagnostic plots, chain autocorrelation estimates, the single-chain convergence test of Geweke (1992), and the stationarity and half-width tests of Heidelberger & Welch (1983).

Table 6: Annual cycle of the west coast South Island hake stock assessment model, 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 frequencies (AFs, *Tangaroa*) or length frequencies (LFs, *Kaharoa*), and observer age frequencies (Fishery AFs)).

Month	Catch (%)		Biology						Observations		Time step
	Actual	Assumed	Ageing	Recruitment	Maturation	Growth (%)	Natural mortality	Spawning	Resource surveys (biomass and Afs/LFs)	Fishery AFs	
Year start			X								1
Oct	1			X							
Nov	0										
Dec	0										
Jan	0	0				0.0	0.67		*Kaharoa* (15 @ 1992–2021)		
Feb	0										
Mar	0										
Apr	0										
May	1										
Jun	23										2
Jul	34	100			X	0.5	0.33	X	*Tangaroa* (6 @ 2000–2021)	X	
Aug	25										
Sep	15										
Year end											
Total	100	100				1.00	1.00				

Table 7: The assumed priors for key distributions (when estimated) for the west coast South Island hake stock assessment. The parameters are mean (in natural space), coefficient of variation (CV) for lognormal, and standard deviation (SD) for normal.

Parameter description	Distribution	Parameters		Bounds	
B_0	Uniform-log	–	–	5 000	350 000
Year class strengths	Lognormal (μ, CV)	1.0	1.1	0.01	100
Trawl survey q*	Lognormal (μ, CV)	0.09	0.79	0.01	1.00
Selectivities	Uniform	–	–	1	25–200†
M	Normal (μ, SD)	0.19	0.05	0.05	0.40

* Three trawl survey q values were estimated, but all had the same priors.
† A range of maximum values was used for the upper bound.

3. RESULTS

3.1 Base model MPD results

A base case model that updated the 2019 model (Kienzle et al. 2019) was developed. This included revised trawl survey biomass estimates using the core strata and new biomass and age frequency (i.e., for ages 5+) for the 2021 survey observations that occurred after the last assessment, as well as new commercial catch data for the 2019–2021 fishing years. The base case model of Kienzle et al. (2019) was also revised by updating the proportion growth and mortality in the annual cycle to be at the midpoint of the second (winter) time step.

The resulting estimated MPD stock trajectories for the base case model are given in Figure 8. Model fits to the survey biomass indices (Figure 9) and age frequencies (Figure 10 and Figure 11) were adequate and did not suggest any strong evidence of departure from model assumptions, as were the fits to the commercial catch-at-age data for the deep (Figure 12 and Figure 13), north shallow (Figure 14 and Figure 15), and south shallow (Figure 16 and Figure 17) fisheries.

Selectivity parameters (Figure 18) were reasonable, with some evidence of a slight decline in the right-hand limb of the *Tangaroa* trawl survey series, but a much steeper decline in the right-hand limb for the *Kaharoa* survey series (when used). The logistic fit to the commercial catch-at age-proportions estimates fish at about age eight to be fully selected, similar to the maturity ogive assumed, suggesting that the fishery was concentrated on adult fish.

The relative year class strengths are plotted in Figure 19. This indicated a period of slightly stronger year classes in the early 1980s and again in the early 1990s. Since then, year classes have been below average with little variation. Data from the trawl surveys and the commercial proportions-at-age data were consistent with the estimated year classes, with the observations of stronger year classes from those years showing in both the observed trawl survey and commercial catch-at-age proportions until the mid-2000s.

Little information was available in the model to estimate the stock recruitment relationship, as the population trajectory had not previously declined to a point where the stock recruitment relationship would impact observed year classes and hence be estimable. Hence the assessment model assumed the steepness (h=0.84), but a sensitivity of h-=0.7 was also investigated. The stock recruitment relationship and estimated recruitments are given in Figure 20.

MPD profiles on B_0 (Figure 21), however, suggested that the information contained in the model observations about the absolute level of biomass was consistent with both the biomass indices and the age frequencies from the survey and the commercial age data.

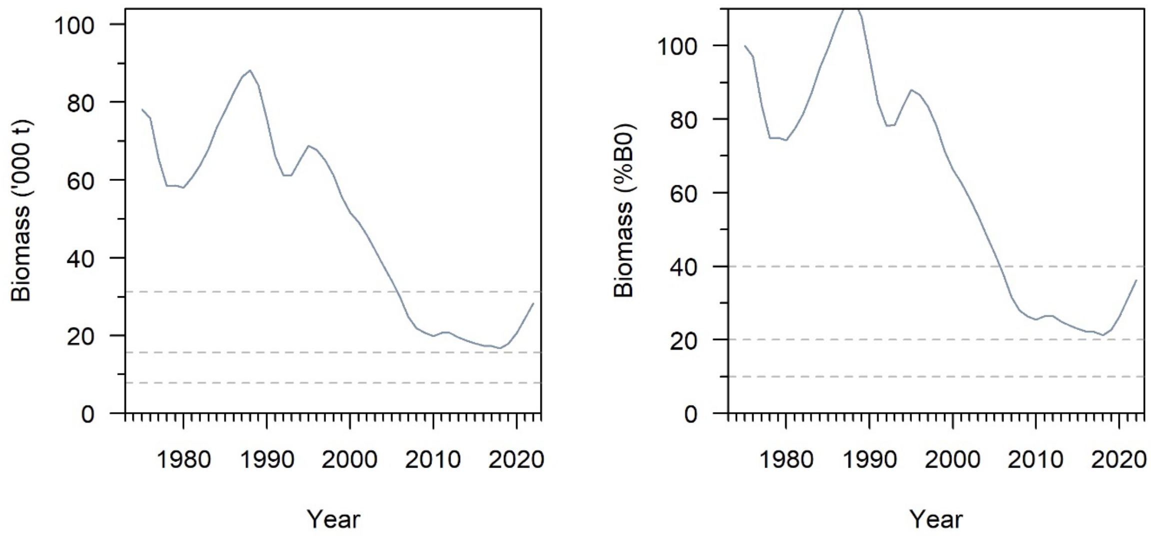

Figure 8: Base case model MPD trajectories for (left) *SSB* biomass and (right) stock status (*SSB*) as a percent of B_0.

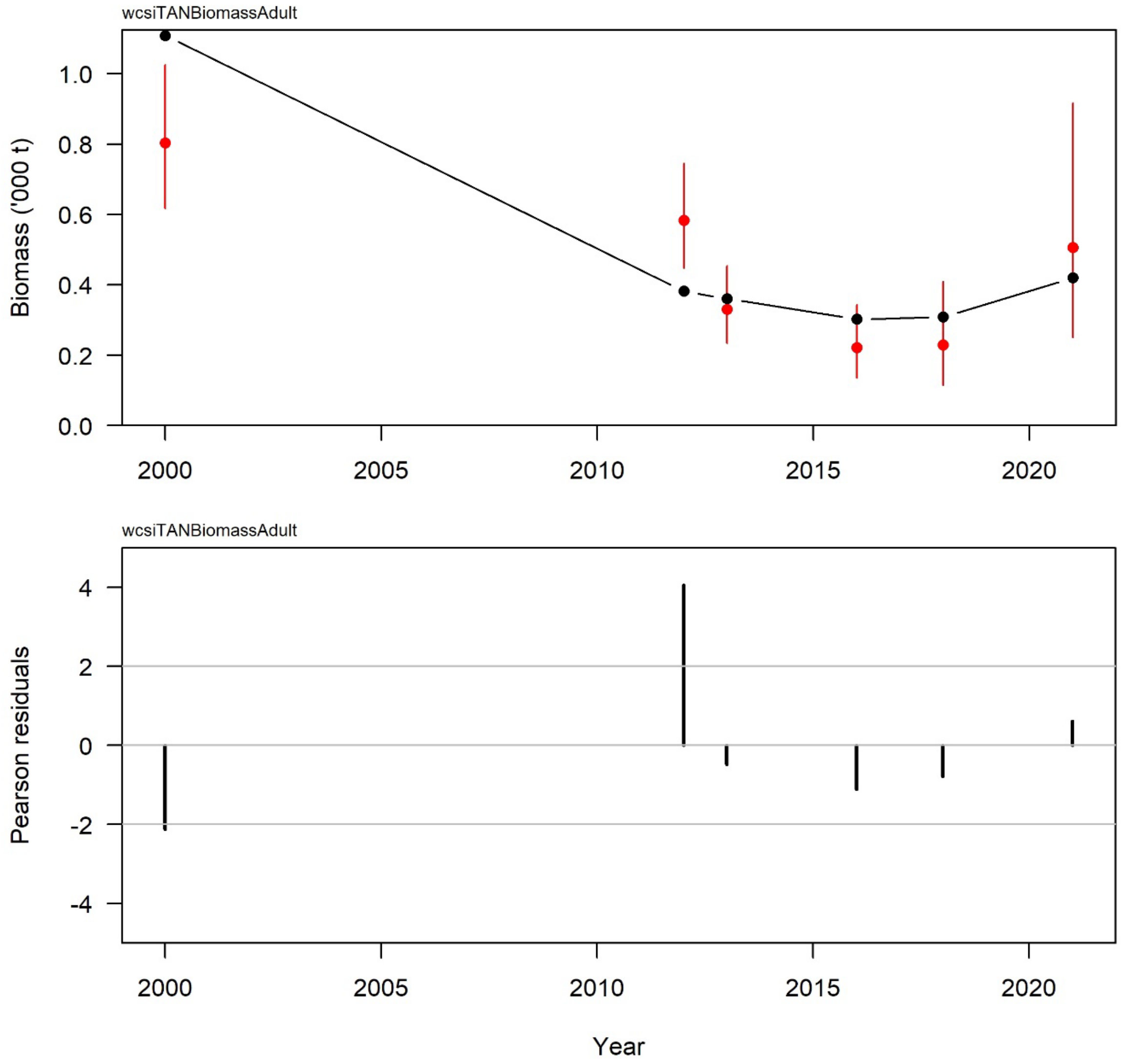

Figure 9: Base case MPD model fits to the *Tangaroa* survey time series for (top) observed biomass (red circles and 95% credible intervals indicated by the red lines) and expected values by black points; and (bottom) Pearson residuals by year for the model fits.

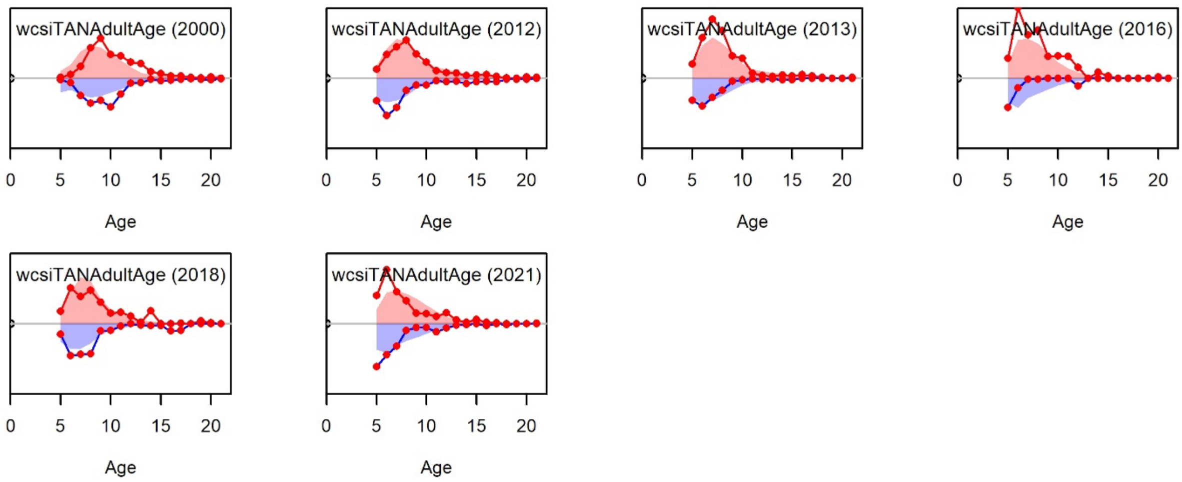

Figure 10: Base case model observed (red points and lines) and expected (shaded red=female and blue=male polygons) proportions-at-age data from the *Tangaroa* survey time series for 2000–2021.

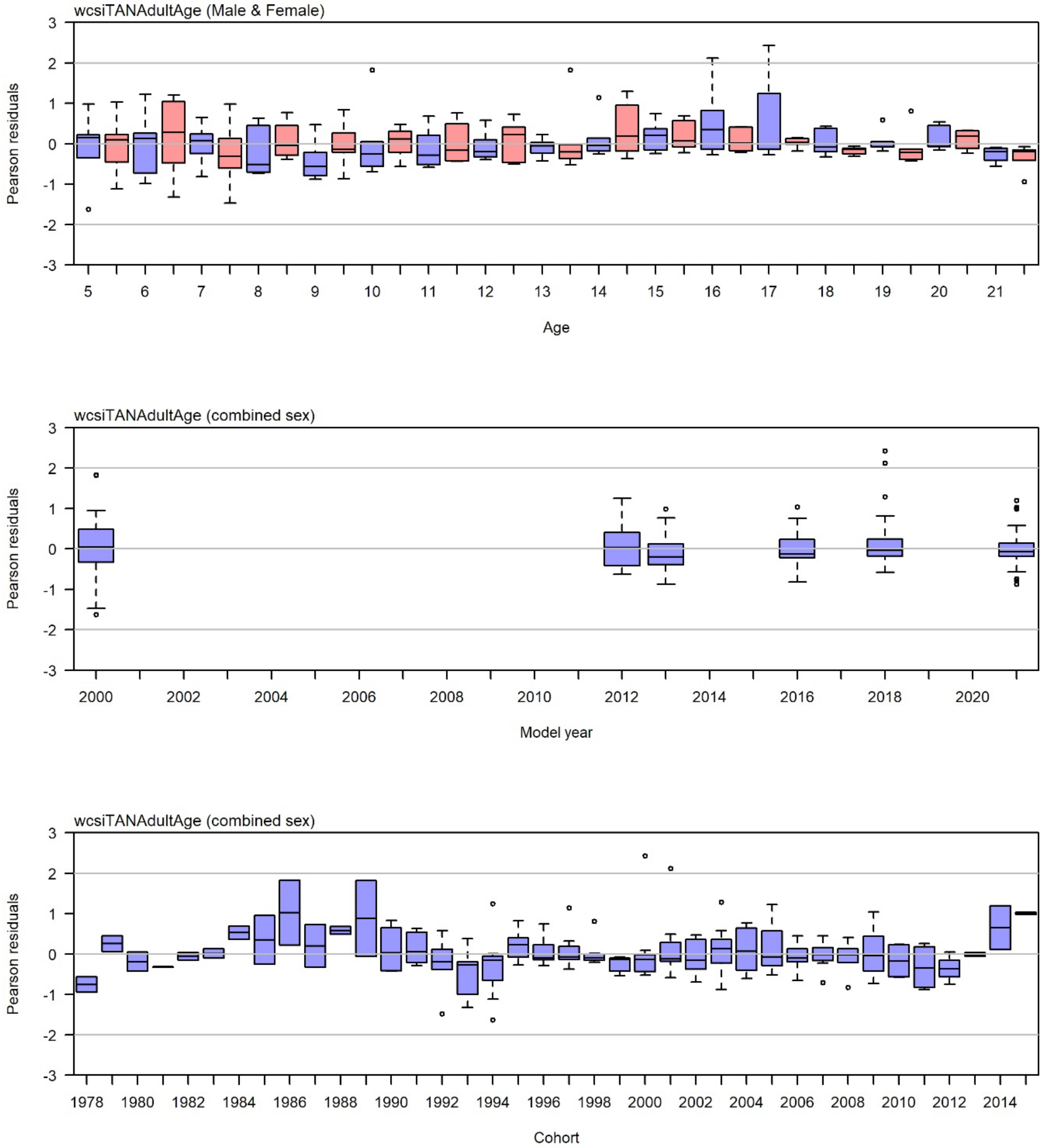

Figure 11: Pearson residuals for the base case MPD model fits to the proportions-at-age data from the *Tangaroa* survey time series for (top) observed age, (middle) year of observations, and (bottom) cohort observed (solid black lines indicate the median, blue boxes the interquartile range, vertical lines are 1.5 times the interquartile range, and black circles are observations outside 1.5 times interquartile range).

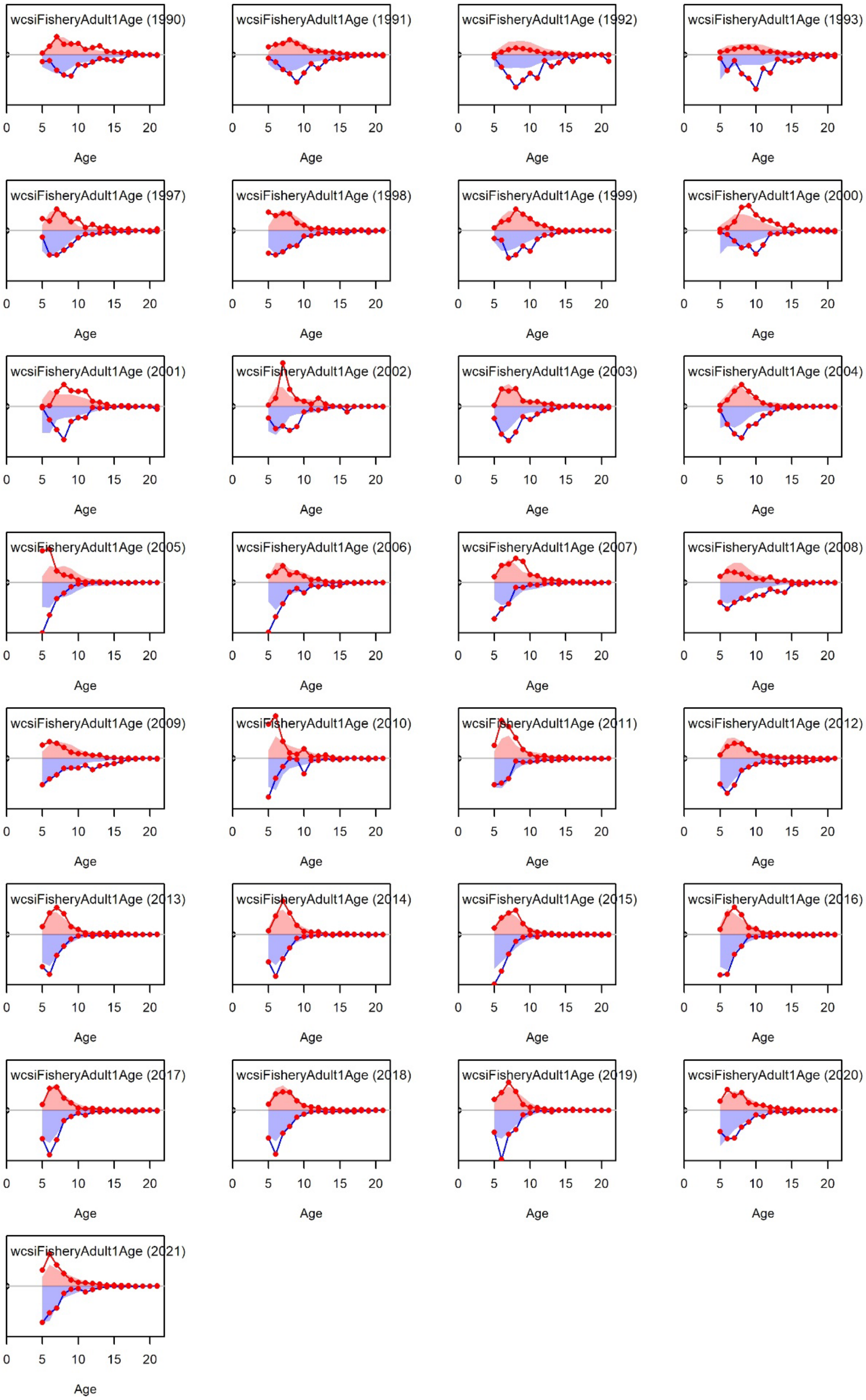

Figure 12: Base case model observed (red points and lines) and expected (shaded red=female and blue=male polygons) proportions-at-age data from the commercial catch-at-age time series for the deep stratum for 1990–2021.

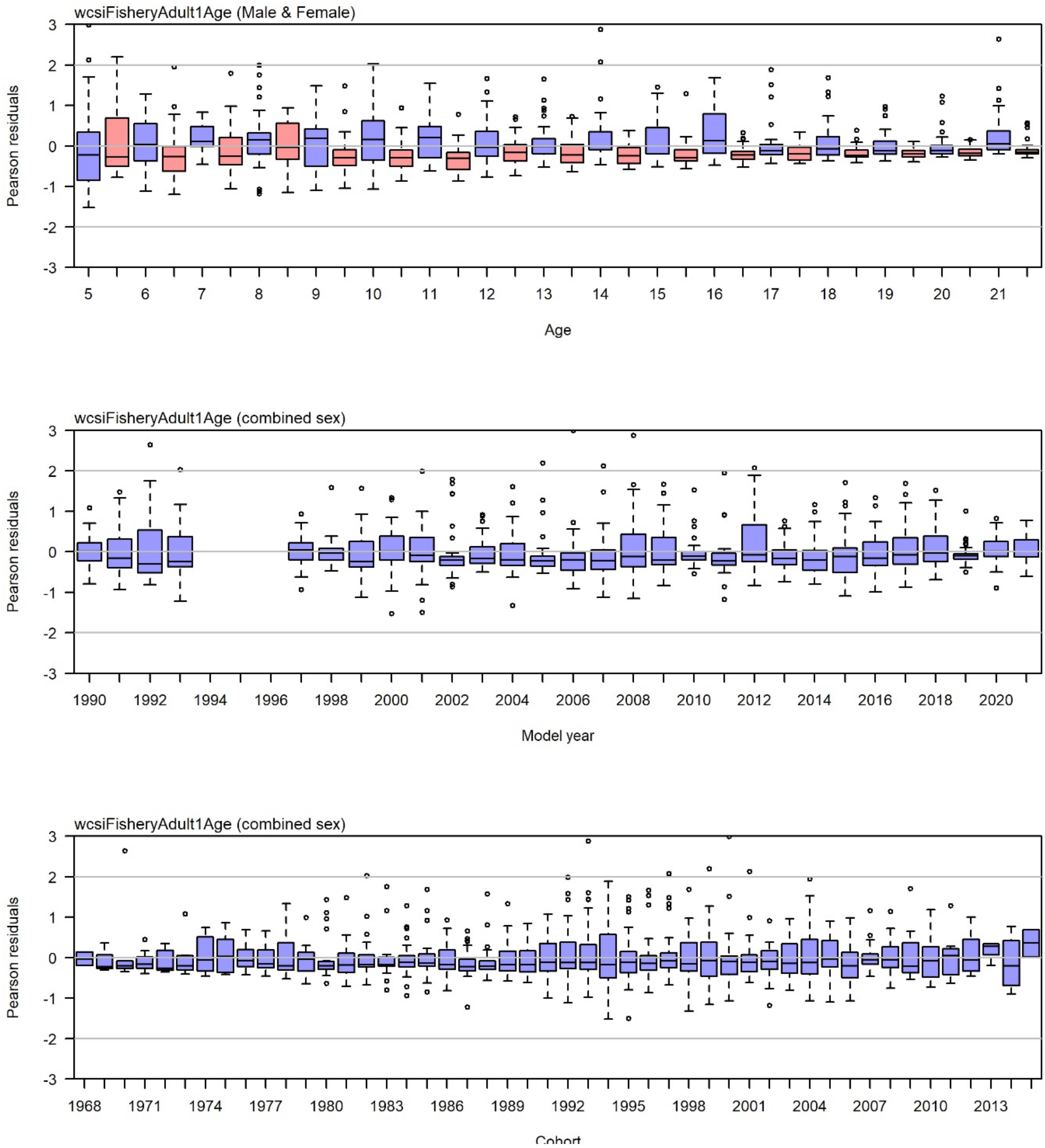

Figure 13: Pearson residuals for the base case MPD model fits to the proportions-at-age data from the commercial fishery for the deep stratum for (top) observed age, (middle) year of observations, and (bottom) cohort observed (solid black lines indicate the median, blue boxes the interquartile range, vertical lines are 1.5 times the interquartile range, and black circles are observations outside 1.5 times interquartile range).

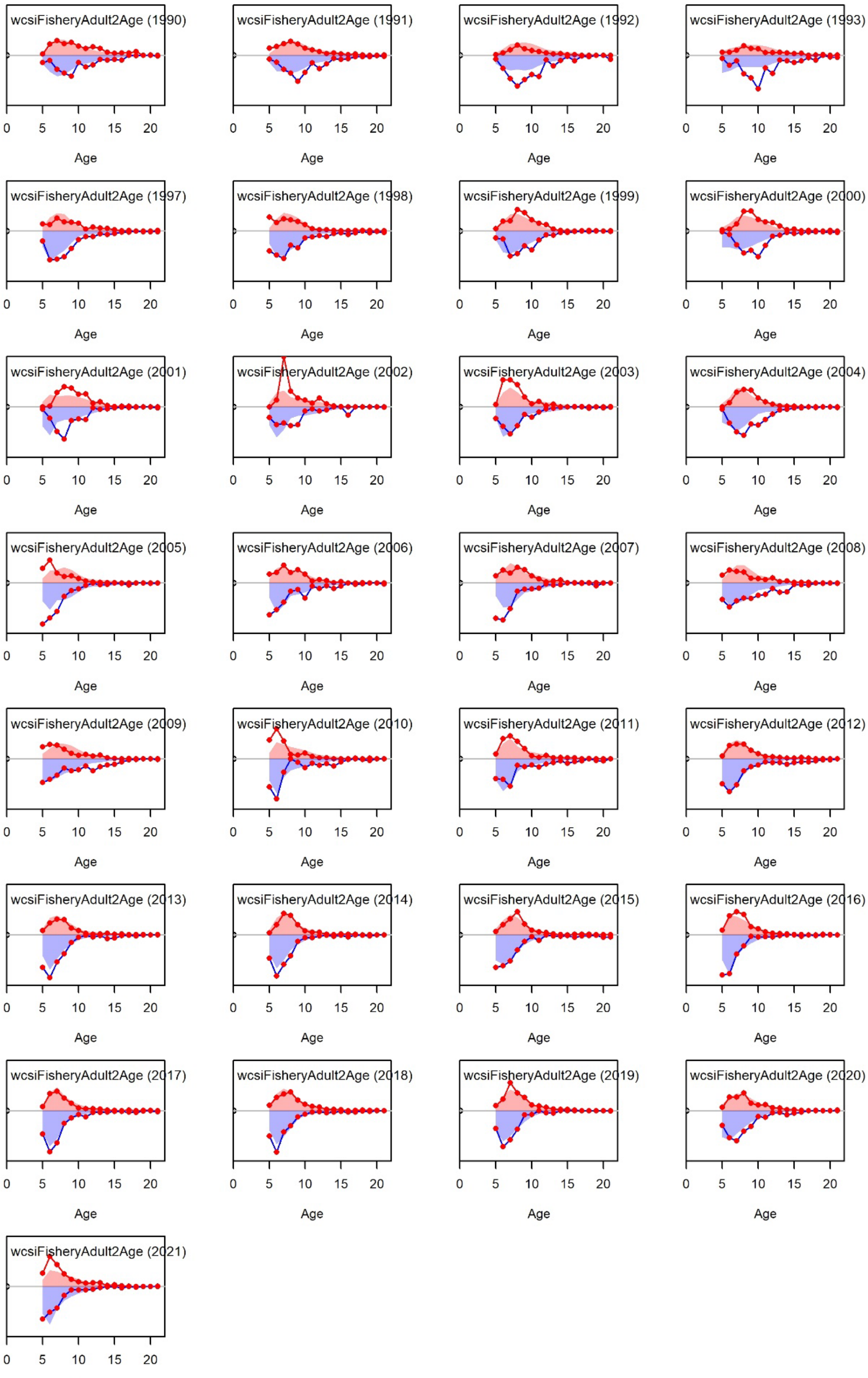

Figure 14: Base case model observed (red points and lines) and expected (shaded red=female and blue=male polygons) proportions-at-age data from the commercial catch-at-age time series for the north shallow stratum for 1990–2021.

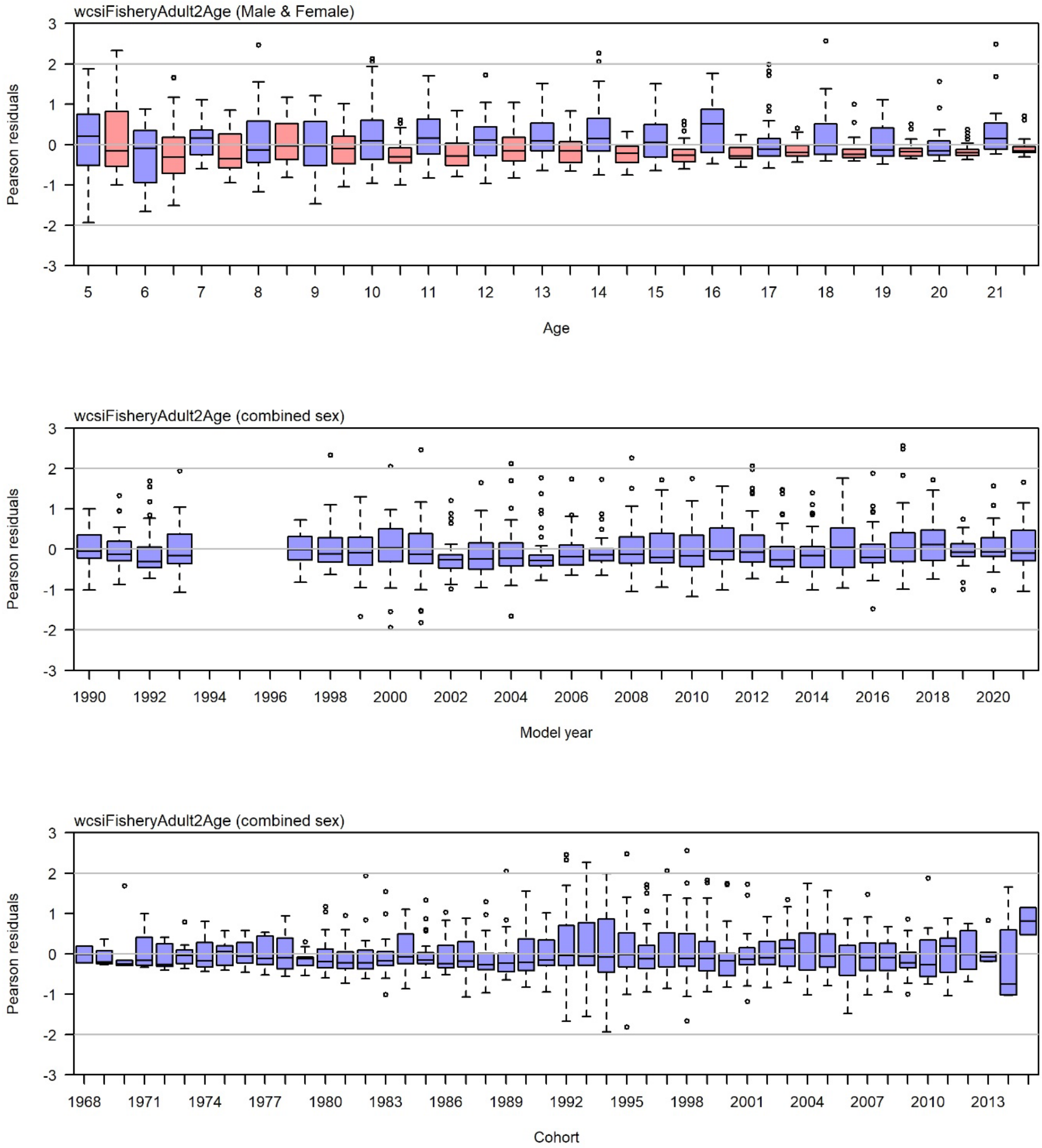

Figure 15: Pearson residuals for the base case MPD model fits to the proportions-at-age data from the commercial fishery for the north shallow stratum for (top) observed age, (middle) year of observations, and (bottom) cohort observed (solid black lines indicate the median, blue boxes the interquartile range, vertical lines are 1.5 times the interquartile range, and black circles are observations outside 1.5 times interquartile range).

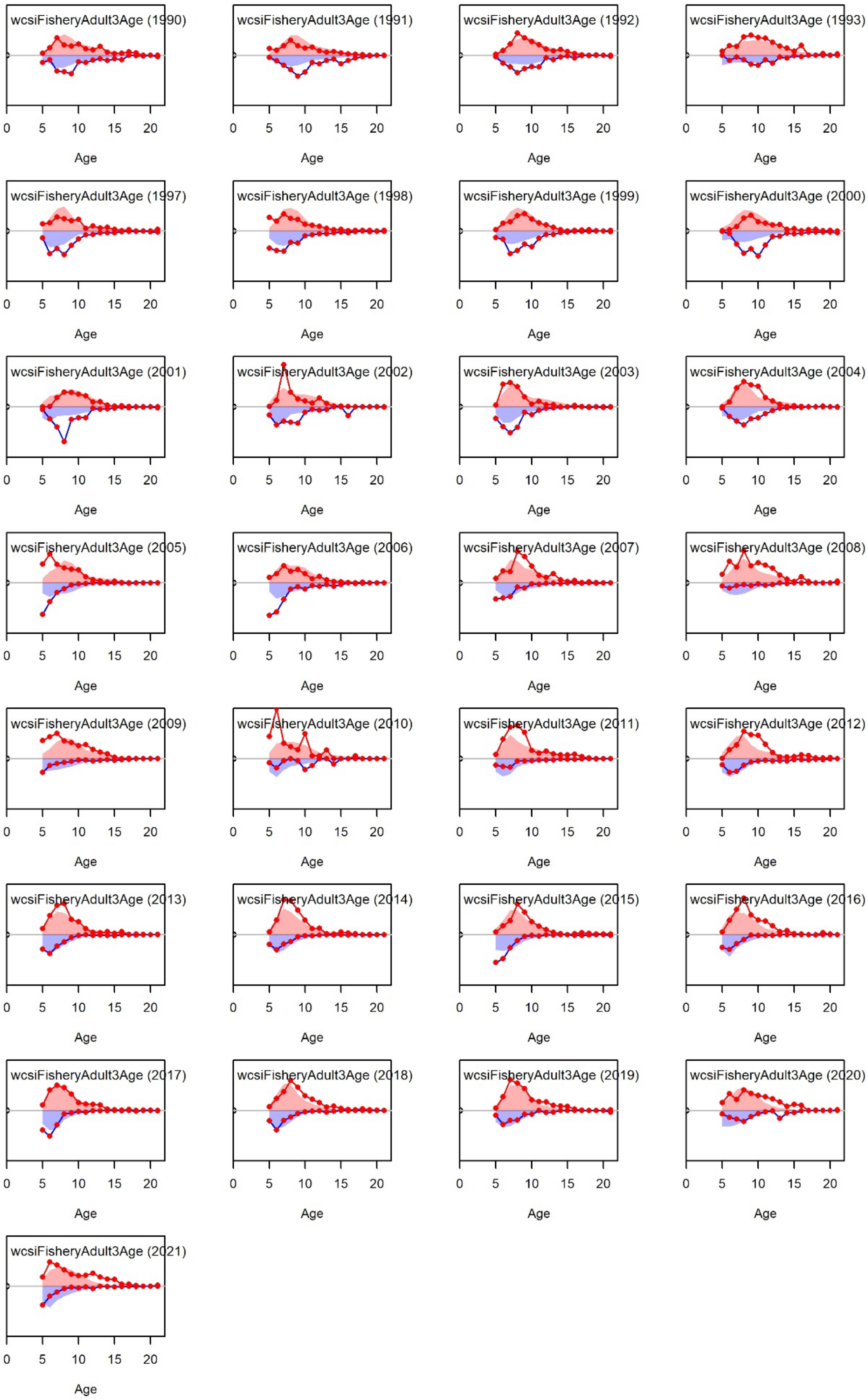

Figure 16: Base case model observed (red points and lines) and expected (shaded red=female and blue=male polygons) proportions-at-age data from the commercial catch-at-age time series for the south shallow stratum for 1990–2021.

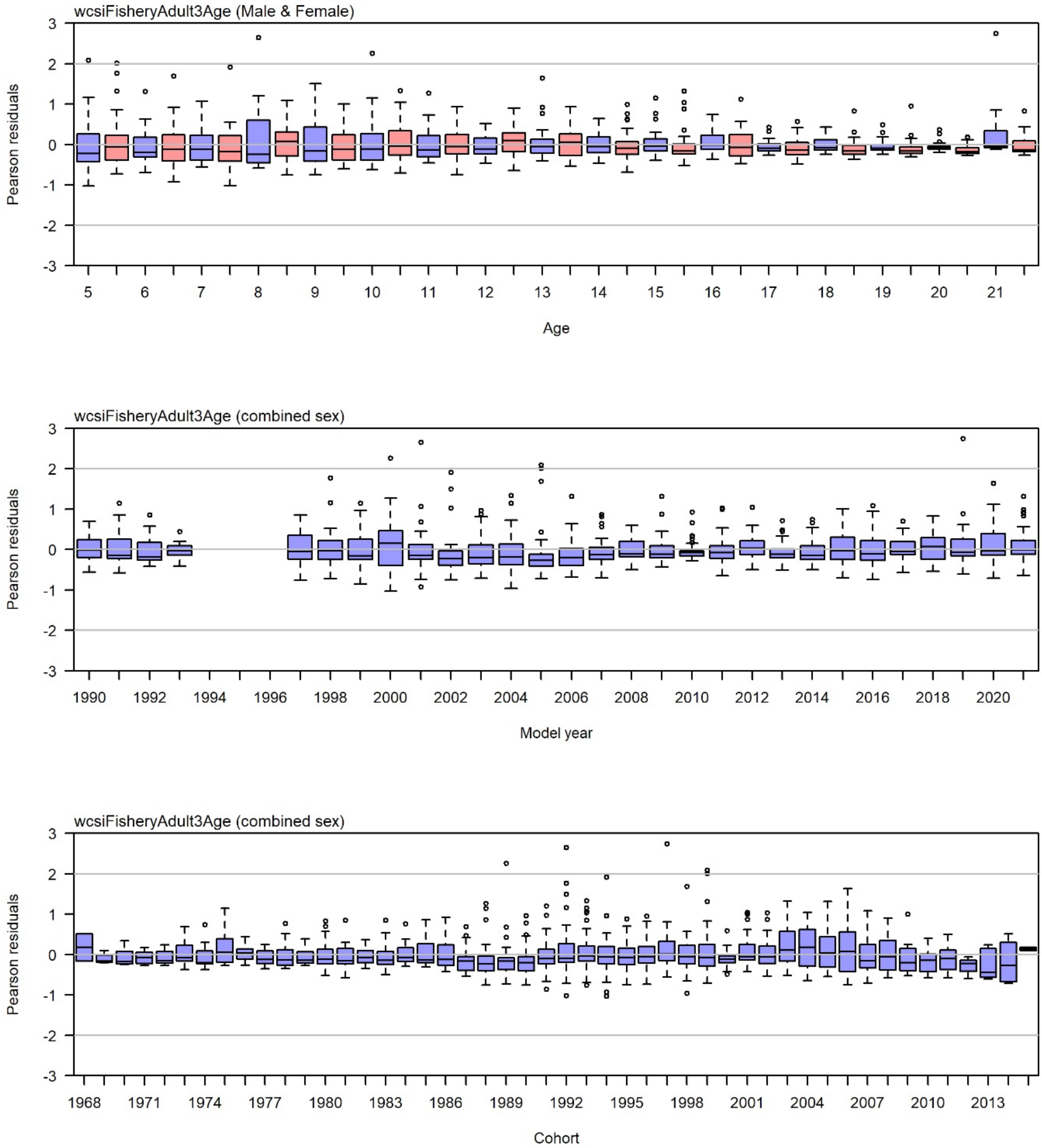

Figure 17: Pearson residuals for the base case MPD model fits to the proportions-at-age data from the commercial fishery for the south shallow stratum for (top) observed age, (middle) year of observations, and (bottom) cohort observed (solid black lines indicate the median, blue boxes the interquartile range, vertical lines are 1.5 times the interquartile range, and black circles are observations outside 1.5 times interquartile range).

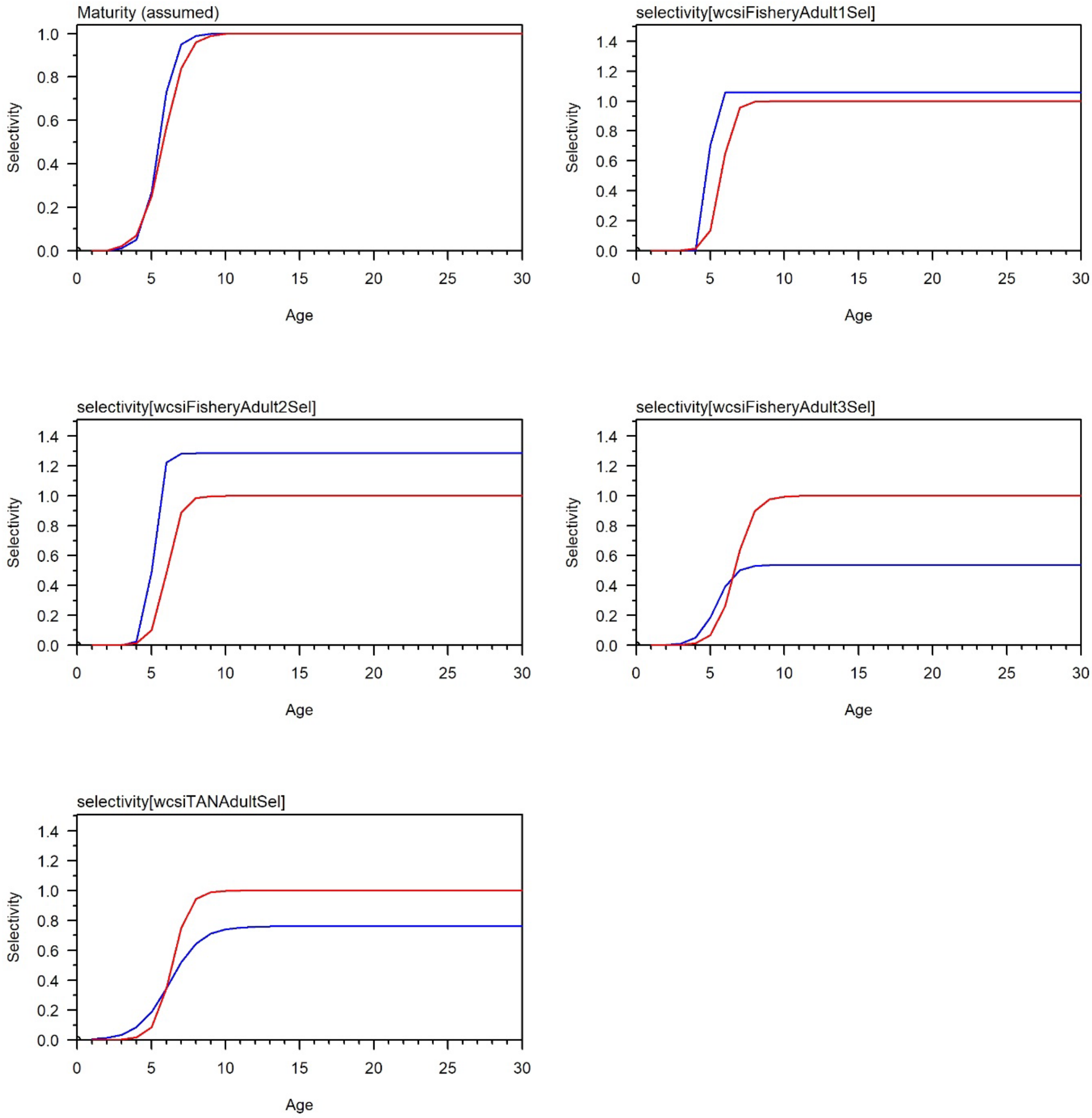

Figure 18: Base case model estimates of the selectivity parameters for the commercial catch selectivities for male (blue) and female (red) hake (deep = wcsiFisheryAdult1, north shallow = wcsiFisheryAdult2, south shallow = wcsiGFisheryAdult3), and the *Tangaroa* survey selectivity (bottom).

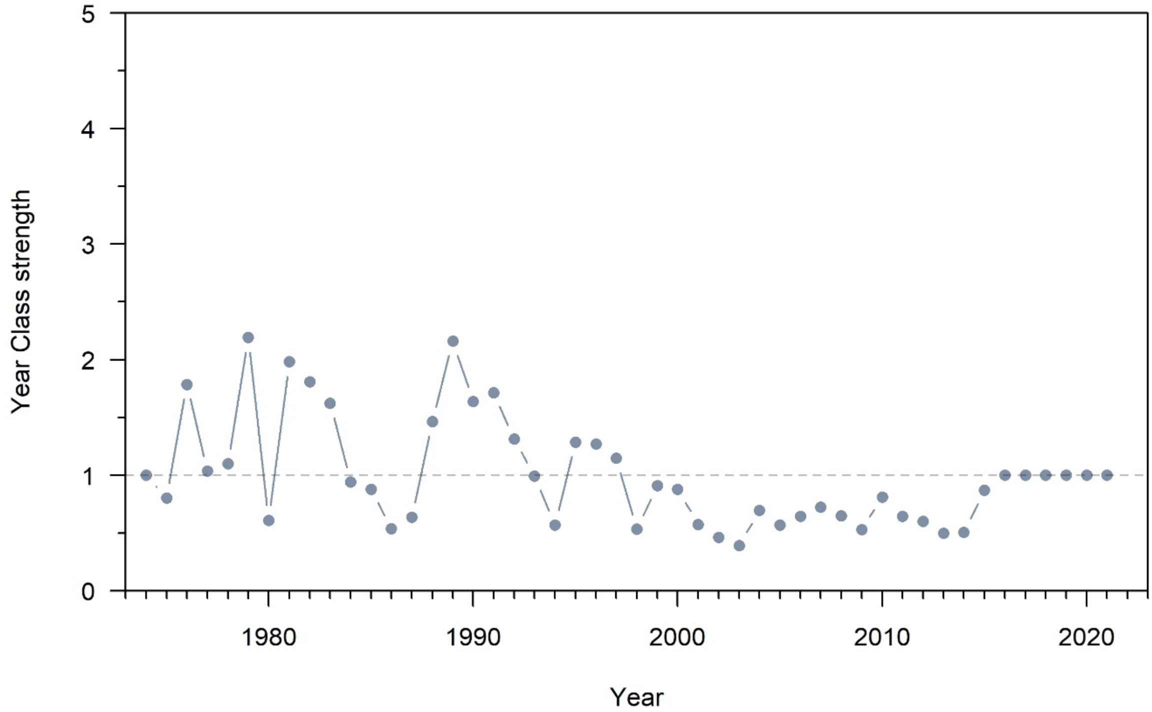

Figure 19: Base case model estimates of the relative year class strength parameters; estimated for 1974–2015 and assumed equal to 1 for 2016–2021.

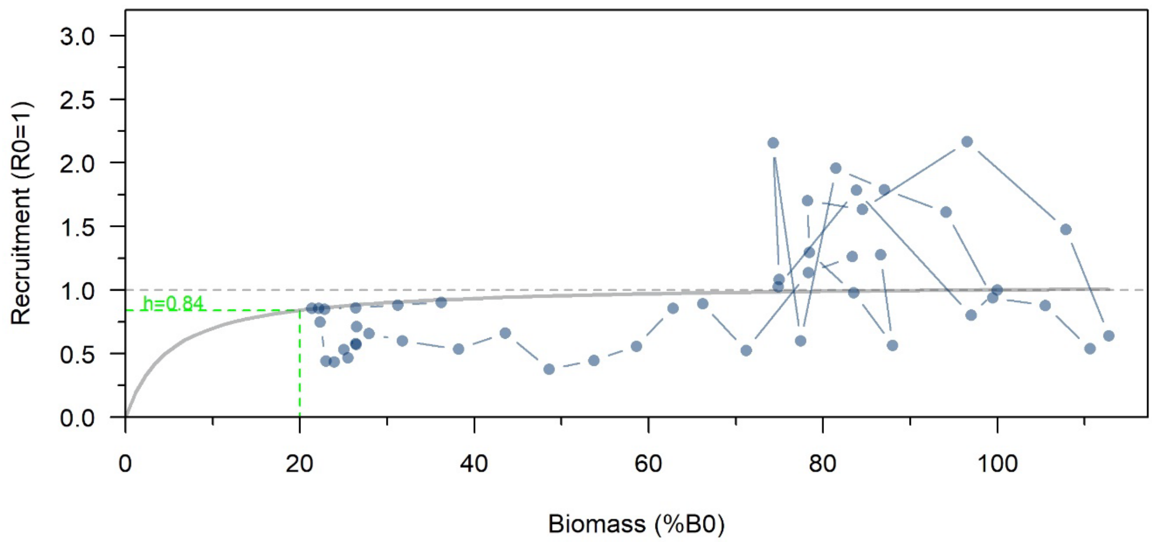

Figure 20: The stock recruitment relationship (Beverton-Holt with steepness $h = 0.84$), and the relative recruitment values (y-axis) plotted against *SSB* (x-axis) for the base case model.

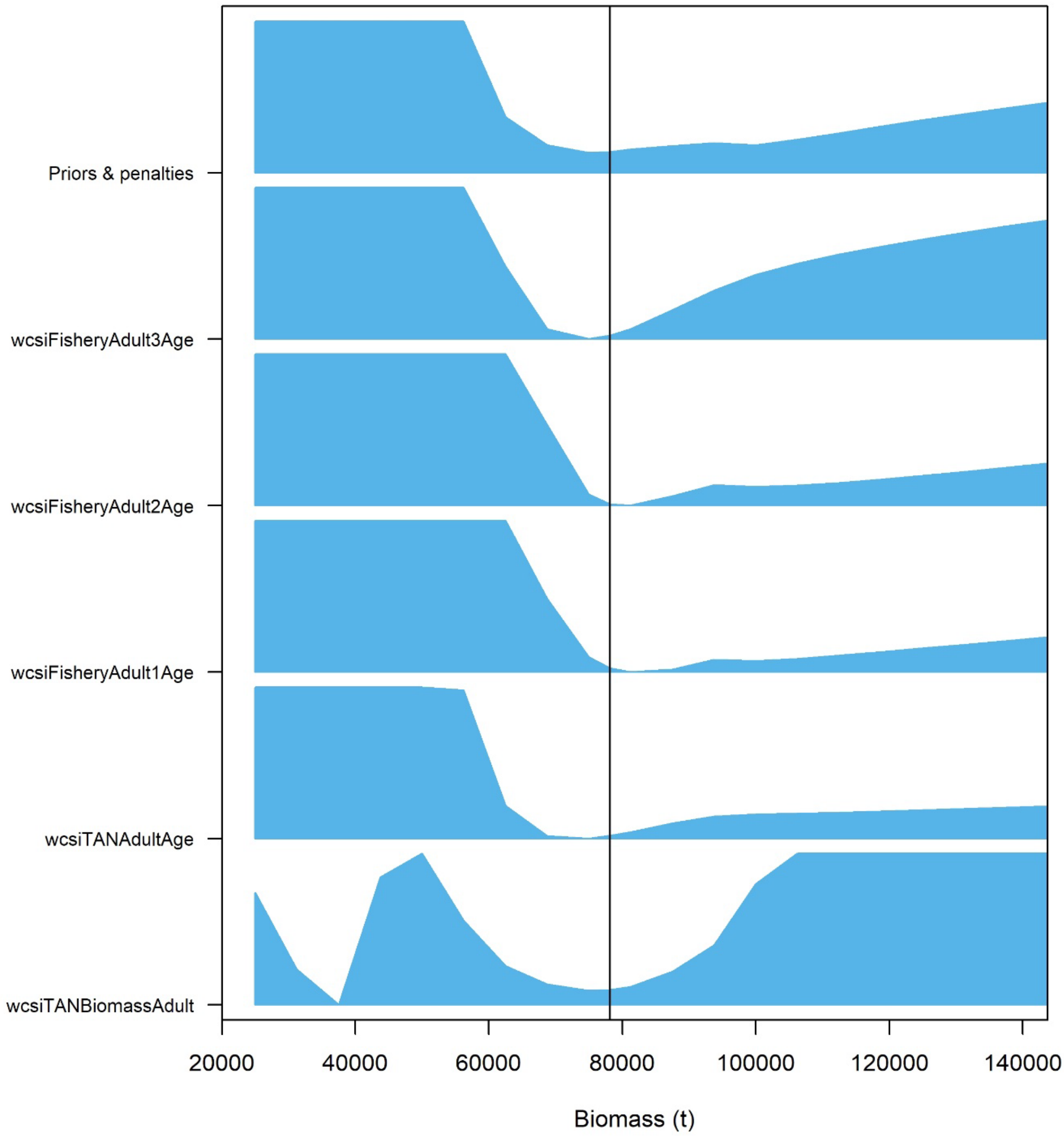

Figure 21: MPD profiles for B_0 using the base case model for the penalties and priors, and each time series of observations. Values were truncated to the maximum height in each graph (10 negative log likelihood (NLL) points).

3.2 Model sensitivities

A range of model sensitives were carried out to evaluate the effect of different model assumptions and choices of data as observations (Table 8). The base case model was used as the initial point for the sensitivities. In general, most sensitives suggested a similar initial and current status as the base case, with the exception of the models that fixed early year class strength to one (model 2: Fix early YCS, defined as prior to 1985). Here, although initial biomass was estimated as similar to the base case, the stock did not deplete as much and current status was subsequently higher.

Including the *Kaharoa* survey (model 7) had little impact, as did assuming a double normal selectivity for the *Tangaroa* survey (model 8), excluding the 2000 survey data (model 9), splitting the south fishery into two fisheries (before 2007, and since 2007, model 10), assuming a stock recruit steepness (h) of 0.7 instead of the assumed 0.8 (model 12), or downweighting (model 13) or upweighting (model 14) the *Tangaroa* survey biomass indices. Estimating M (model 11) led to an average male and female estimate of 0.185 y^{-1} instead of the assumed 0.19 y^{-1}, but the sex-specific estimates were implausible (0.23 y^{-1} for males and 0.14 y^{-1} for females).

Sensitivities that were most influential on current status were assumptions of recent year class strengths. When year classes were estimated up to 2014 (model 5) or 2016 (model 6), the stock status in 2022 increased from 36% to 49% B_0; the strength of recent year classes (for which there were few, if any, observations) was highly influential on the level of stock rebuild in the fishery in recent years.

However, while the sensitivities altered the outcome of the base case model in the extent of the rebuild since about 2016, all models suggested a significant increase since then, with the sensitivities indicating a stock status of between 30 and 70% B_0 (Table 8) and rebuilding from a low point in about 2016.

Table 8: Sensitivity models (MPD) to the 2022 base case stock assessment model for west coast South Island hake for 2018 and current (2022) status. YCS is year class strength, KAH is the *Kaharoa* survey.

Model		B_0	B_{2018}	B_{2018} (% B_0)	B_{2022}	B_{2022} (% B_0)
1	Base case	78 202	17 842	22.8	28 314	36.2
2	Fix early YCS (<1985)	83 089	38 950	46.9	58 641	70.6
3	Low M (0.15 y^{-1})	79 325	15 025	18.9	23 776	30.0
4	High M (0.23 y^{-1})	85 859	21 955	25.6	35 544	41.4
5	Estimate YCS up to 2014	78 637	18 950	24.1	30 101	38.3
6	Estimate YCS up to 2016	81 289	22 000	27.1	40 031	49.2
7	Include the KAH survey	75 105	12 485	16.6	21 222	28.3
8	Survey domed selectivity	78 801	18 070	22.9	28 472	36.1
9	Exclude the *Tangaroa* 2000 biomass data	77 771	14 488	18.6	24 166	31.1
10	Split the south shallow fishery into <2007 & 2007+	79 226	19 449	24.5	30 401	38.4
11	Estimate M and split the south shallow fishery	75 959	16 804	22.1	26 544	34.9
12	Assume SR h = 0.7	80 791	17 266	21.4	25 851	32.0
13	Additional CV=0.2 for the survey	78 361	17 344	22.1	27 776	35.4
14	Reduce the CV=0.1 for the survey	78 123	18 283	23.4	29 976	38.4
15	Base+	79 848	18 205	22.8	28 900	36.2

3.3 MCMC results

MCMCs were carried out for the base case and the sensitivities. Similar results were obtained for the MCMC estimates as for the same sensitivity at MPD. Estimates of initial biomass (B_0), current biomass (B_{2022}), and current status (B_{2022} as a percent of B_0) are given in Table 9. Estimates of catchability parameters and natural mortality are given in Table 10.

MCMC estimates of year classes were uncertain in the initial years, but replicated the pattern seen in the MPDs of large year class strengths in the late 1970s and 1980 and showed average with low variability thereafter (Figure 22). Model estimates of initial biomass and current biomass (Figure 23) were relatively symmetric, and comparisons of MCMC chains did not indicate any evidence of non-convergence. Estimates of the trawl survey catchability (Figure 24) were within the priors but were concentrated at the bottom end of the prior, indicating low catchability of the surveys. Expected MCMC values for the *Tangaroa* survey biomass indices (Figure 25) were reasonable and indicated a good fit of the MCMCs to the abundance biomass data. Model estimates of the selectivity parameters (Figure 26) indicated good evidence that the relative selectivity of males and females differed in the survey and in the three fisheries.

The base case model suggested an initial spawning stock biomass of 59 000 t (95% C.Is. 43 220–93 600 t) and current biomass of 36 490 t (95% C.I.s 22 250–65 510 t), with a current status of 61.7% (95% C.I.s 49.5–75.1%) (Figure 27).

Model convergence diagnostics for almost all parameters were adequate, with the exception being the right-hand limb parameters of the two (domed) survey selectivities. Multichain comparisons did not indicate any evidence of non-convergence for the key output parameters (Figure 23). Sensitivity analyses that fixed the right-hand limb parameters of the survey selectivities did not suggest any significant change in output quantities. Although better MCMC performance for these parameters would be ideal, the poor traces and issues with determining convergence was not significant in the interpretation of the model outcomes.

Table 9: Estimates (t) of B_0 and current status for the base case and sensitivity models for the west coast South Island hake assessment model. OBS is observer data, YCS is year class strength, AF is age frequency, TAN is *Tangaroa* survey, KAH is *Kaharoa* survey.

Model		B_0	B_{2022}	B_{2022} (% B_0)
1	Base case	78 870 (74 140–84 810)	30 350 (22 450–43 390)	38.6 (29.5–52.2)
2	Fix early YCS (<1985)	81 680 (74 440–92 170)	54 080 (35 390–80 350)	66.1 (47.5–87.4)
3	Low M (0.15 y^{-1})	80 020 (76 550–84 670)	25 140 (18 080–36 640)	31.4 (23.3–43.5)
4	High M (0.23 y^{-1})	85 650 (78 710–94 600)	38 580 (29 070–53 920)	45.1 (35.3–59.4)
5	Estimate YCS up to 2014	79 100 (74 820–84 520)	31 270 (26 130–38 710)	39.5 (34.0–47.0)
6	Estimate YCS up to 2016	80 960 (75 340–88 660)	37 960 (24 290–61 010)	47.1 (31.5–69.8)
7	Include the KAH survey	75 340 (71 590–79 840)	22 440 (17 950–28 410)	29.8 (24.4–36.7)
8	Survey domed selectivity	79 280 (74 350–85 420)	30 980 (22 640–44 070)	39.1 (29.7–52.7)
9	Exclude the *Tangaroa* 2000 biomass data	78 210 (73 860–83 950)	26 070 (19 940–36 600)	33.4 (26.3–44.9)
10	Split south shallow into <2007 & 2007+	79 820 (74 740–86 340)	32 460 (23 790–46 970)	40.7 (30.9–55.6)
11	Estimate M and split south shallow	77 970 (72 970–88 840)	31 440 (20 830–49 290)	40.4 (27.5–56.9)
12	Assume SR h = 0.7	81 600 (76 800–87 610)	27 710 (19 650–40 650)	34.0 (25.1–47.0)
13	Additional CV=0.2 for the survey	79 180 (74 370–85 390)	30 580 (21 830–44 740)	38.6 (28.6–53.7)
14	Reduce the CV=0.1 for the survey	77 720 (73 800–82 380)	28 840 (23 890–35 350)	37.1 (31.3–44.2)
15	Base+	80 480 (75 760–86 290)	31 050 (22 880–44 180)	38.6 (29.4–52.4)

Table 10: Estimates of survey catchability estimates for the base case and sensitivity models for the west coast South Island hake assessment model. YCS is year class strength, KAH is *Kaharoa* survey.

Model		*Tangaroa* survey q	*Kaharoa* q
1	Base case	0.029 (0.021–0.042)	
2	Fix early YCS (<1985)	0.029 (0.020–0.054)	
3	Low M (0.15 y^{-1})	0.035 (0.026–0.051)	
4	High M (0.23 y^{-1})	0.024 (0.017–0.034)	
5	Estimate YCS up to 2014	0.029 (0.021–0.042)	
6	Estimate YCS up to 2016	0.029 (0.021–0.040)	
7	Include the KAH survey	0.032 (0.023–0.048)	0.447 (0.089–0.945)
8	Survey domed selectivity	0.029 (0.021–0.046)	
9	Exclude the *Tangaroa* 2000 biomass data	0.032 (0.023–0.046)	
10	Split south shallow into <2007 & 2007+	0.028 (0.021–0.041)	
11	Estimate M and split south shallow	0.039 (0.026–0.070)	
12	Assume SR h = 0.7	0.029 (0.021–0.044)	
13	Additional CV=0.2 for the survey	0.031 (0.021–0.047)	
14	Reduce the CV=0.1 for the survey	0.030 (0.022–0.045)	
15	Base+	0.028 (0.021–0.040)	

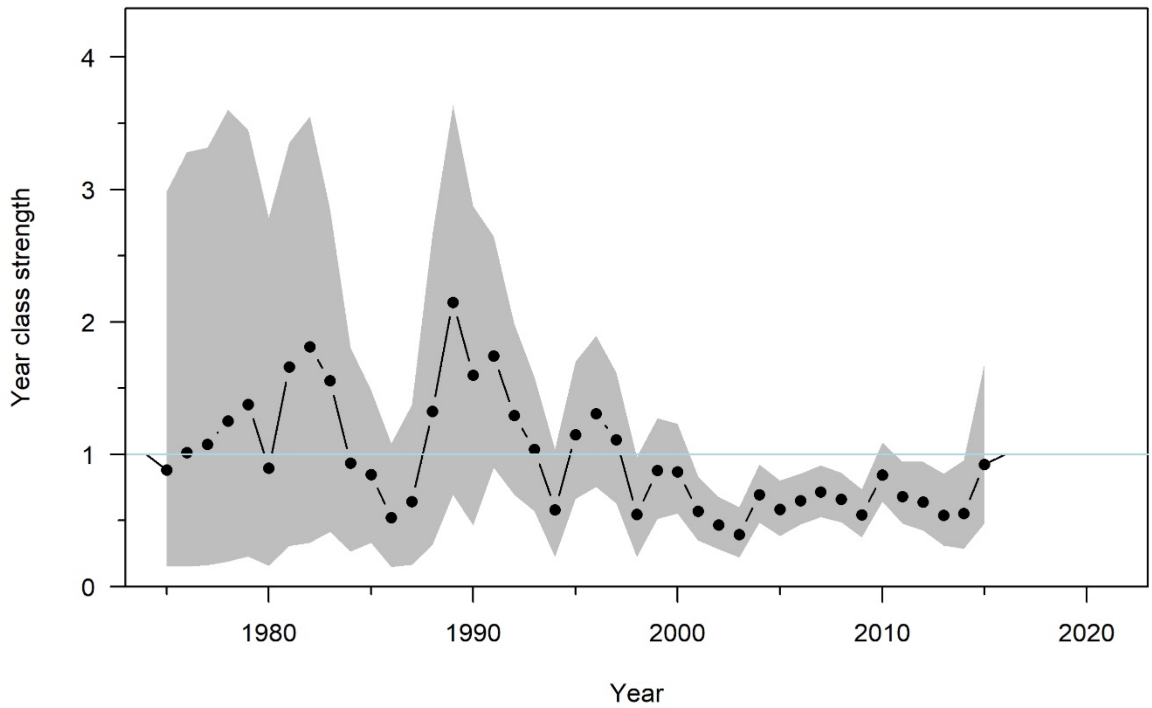

Figure 22: Base case model posterior distribution of year class strengths for years 1975–2015. The points indicate the median and the shaded area represents the 95% credible intervals. The dotted horizontal line indicates the average of one.

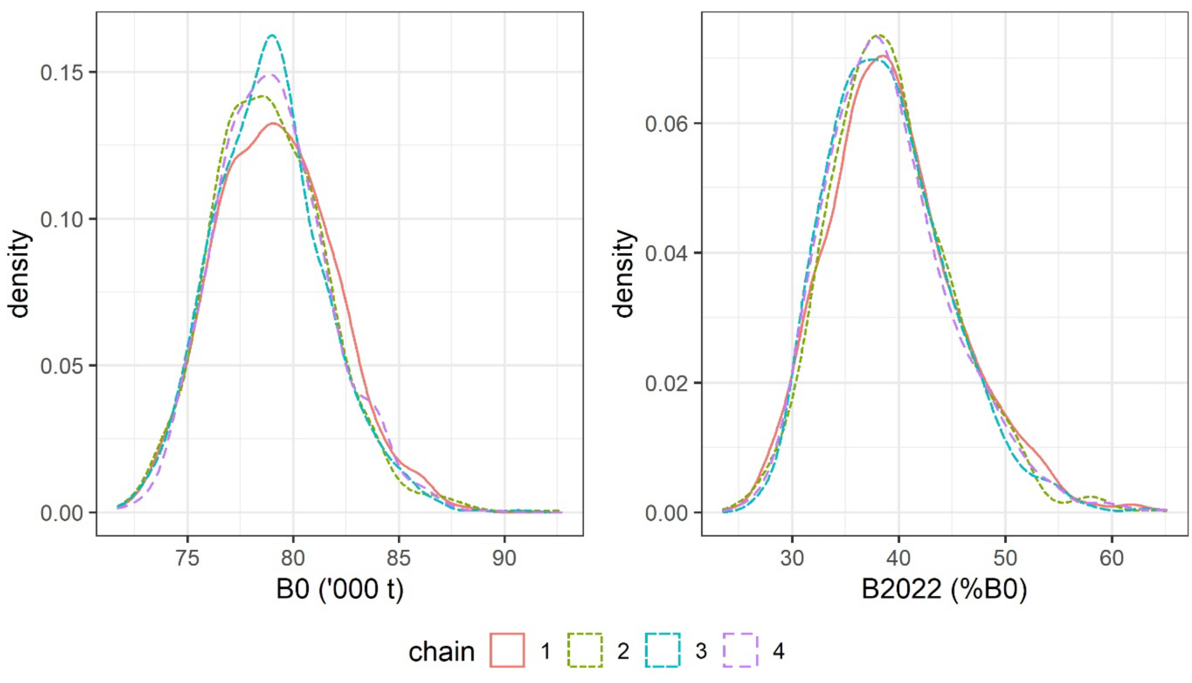

Figure 23: Base case model posterior distribution of (left) B_0 and (right) B_{2022} as a percent of B_0.

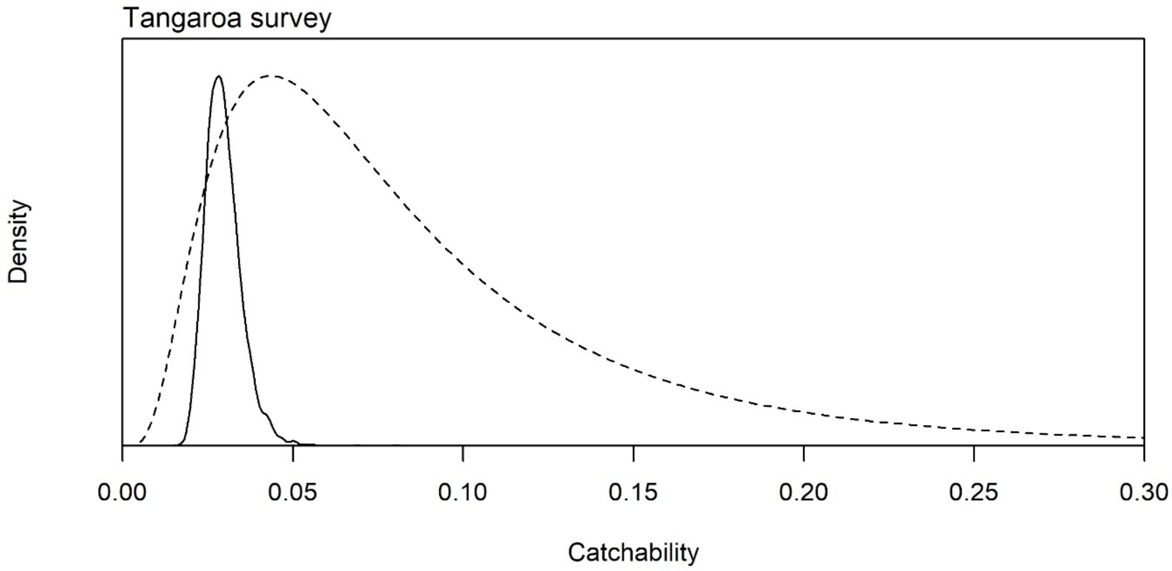

Figure 24: Base case model posterior distribution of the *Tangaroa* series catchability (solid line). The prior for the catchability is shown as a dashed line.

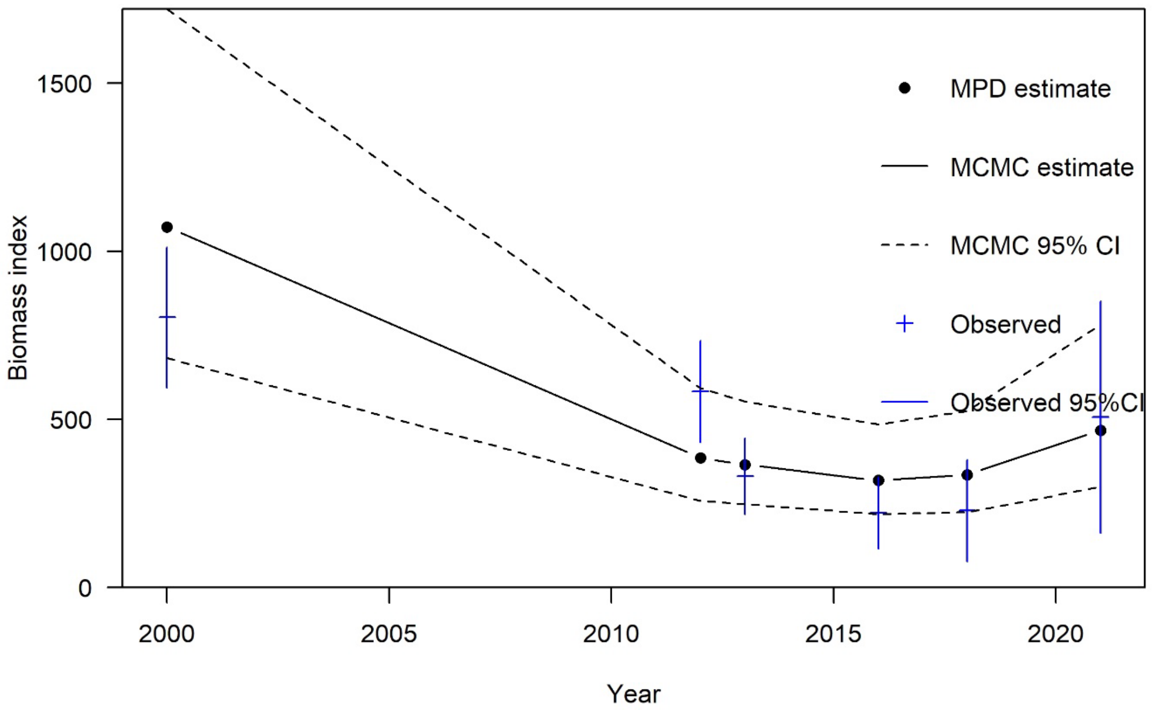

Figure 25: Base case model posterior distribution of the expected values for the *Tangaroa* survey series. Observed values (and 95% confidence intervals) are shown as vertical lines. Dashed lines indicate the 95% credible interval.

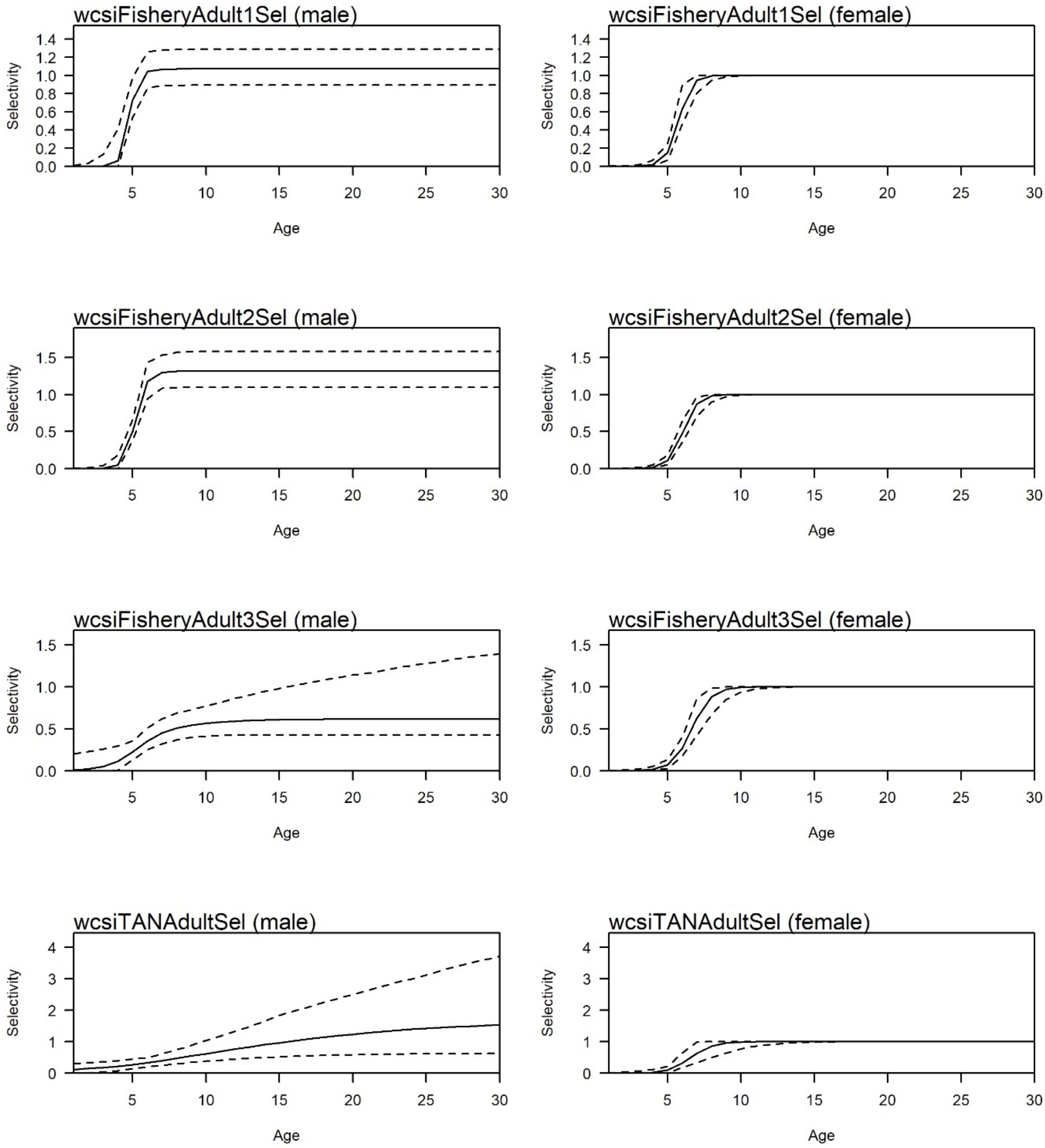

Figure 26: Base case model posterior distribution of the expected values for the commercial catch selectivities (deep = wcsiFisheryAdult1, north shallow = wcsiFisheryAdult2, south shallow = wcsiGFisheryAdult3) and the *Tangaroa* survey selectivity (bottom) for males (left) and females (right). The solid line indicates the median trajectory and the dashed lines indicate the 95% credible interval.

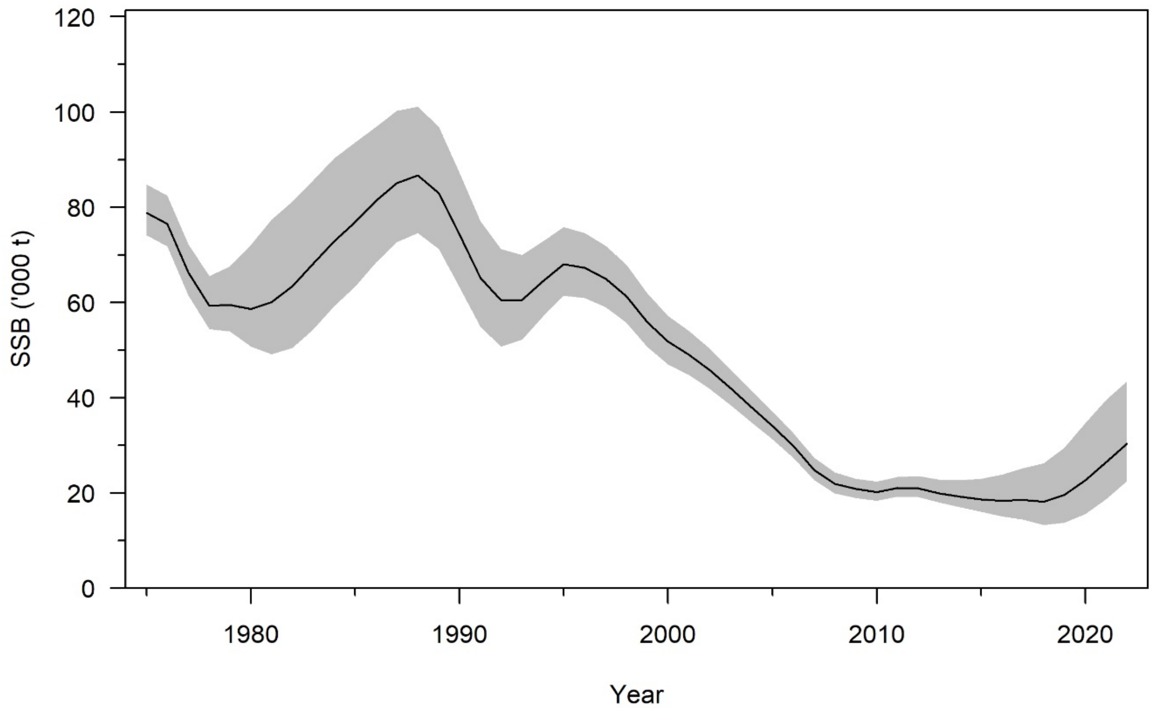

Figure 27: Posterior distribution of the historical (1975–2022) stock biomass (t) for the base case model for west coast South Island hake. The solid line indicates the median trajectory and the shaded area indicates the 95% credible interval.

3.4 Alternative catch history

A plausible alternative catch history for hake that included possible unreported catches and an estimate of discards and small fish mortality resulting from escapement through the fishing net mesh was developed. Data on small fish catch and likely mortality from escapement through net mesh is not known for hake. However, the level of unreported catch prior to the introduction of the Quota Management System (QMS) in 1986 is assumed to be low due to the high commercial value of hake, and hence the fishers are likely to have retained as much catch as possible during that time. More recently, discards are thought to be low—discards from the hoki, hake, and ling (*Genypterus blacodes*) target trawl fishery within the New Zealand EEZ were estimated by Anderson et al. (2019) as 0.42%.

Given the low proportions of likely under-reporting of hake, an approximation that assumed 5% additional fishery mortality for years before the introduction of the QMS and 2% thereafter was run as a sensitivity to the base case model (base+ model). The inclusion of the assumption of additional mortality and pre-QMS unreported catch resulted in estimates of biomass that were only slightly different to the base case above (Figure 28).

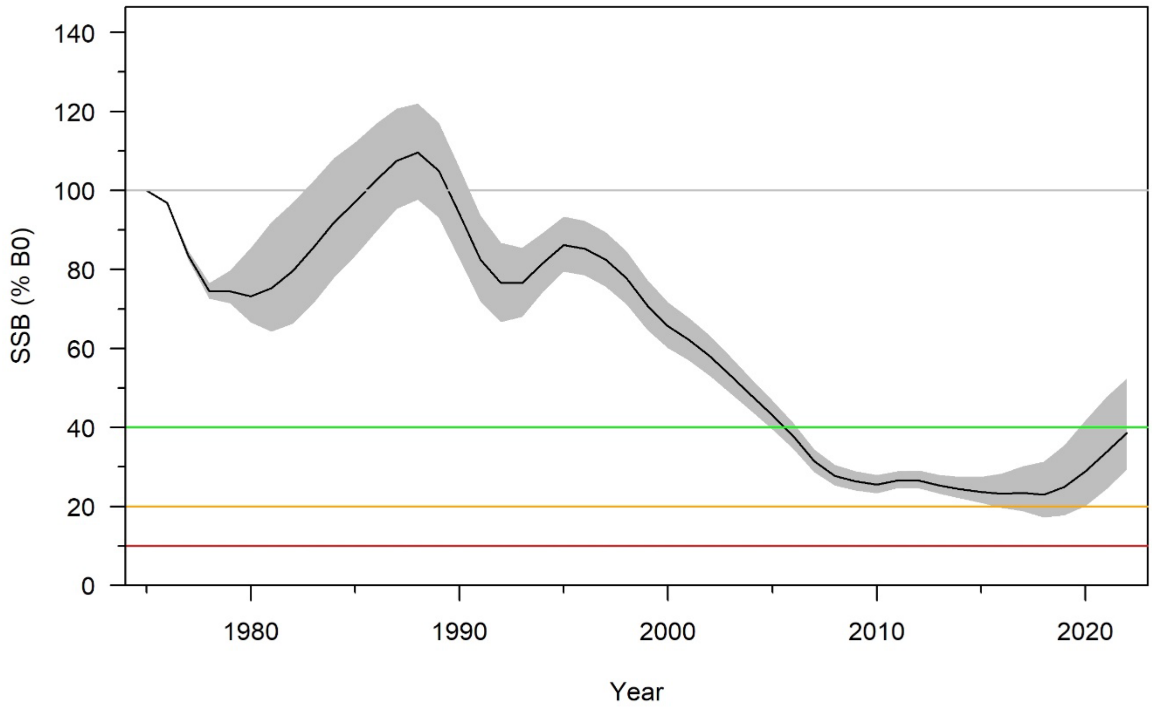

Figure 28: The base+ MCMC stock status trajectory (% B_0) for 1974–2022. The solid line indicates the median trajectory, and the shaded area indicates the 95% credible interval. Horizontal lines indicate the target (green, 40% B_0), soft limit (yellow, 20% B_0), and hard limit (red, 10% B_0), respectively.

3.5 Projections

Four sets of projection runs were carried out whereby the future annual catch for the next five years was set at the level of the current catch (1664 t) or the current TACC for HAK 7 (2272 t). The catch split between the three fisheries was based on the average catch split for the most recent five years of reported catches (2017–2021).

Results are shown in Table 11 for the estimated stock status and in Table 12 for risks of being below target, soft, or hard limits. Figure 29 shows the *SSB* trajectories under the assumption of current catch and recent year class strengths projected for five years into the future, and Figure 30 shows the same projection as percent of B_0. Stock status in 2027 is expected to increase slightly over the next five years under assumptions of both current catch and a catch equal to the HAK 7 TACC and long-term average recruitment.

Table 11: Estimates of B_0 (t) and 95% credible intervals for the estimated projected status (B_{2027} in tonnes or as a percent of B_0) for 2023–2027 for the base case and selected sensitivity models for west coast South Island hake, with assumptions of future recruitment either equal to the average over all years, or the most recent 10 years; and assuming future catch equals either current catch (1664 t) or the TACC (2272 t). YCS is year class strength.

Future catch (t)	Future YCS	B_{2022}	B_{2027}	B_{2027} (% B_0)	B_{2027}/B_{2022} (%)
1. Base case					
1 664	2006–2015	25 820 (16 770–41 850)	31 650 (20 450–50 130)	40.2 (26.8–60.5)	122.4 (105.1–142.3)
2 772		25 820 (16 770–41 850)	29 580 (18 350–48060)	37.5 (24.0–58.0)	114.1 (97.3–133.7)
1 664	1974–2015	30 150 (18 920–47 970)	45 520 (27 840–71 030)	57.7 (36.1–88.5)	148.1 (103.7–230.4)
2 772		30 150 (18 920–47 970)	43 420 (25 740–68 920)	55.0 (33.4–85.8)	141.1 (98.1–222.8)
2. Fixed 1984 YCS					
1 664	2006–2015	53 800 (32 250–87 010)	61 330 (38 040–103 080)	74.8 (50.7–116.3)	114.4 (95.2–146.6)
2 772		53 800 (32 250–87 010)	59 270 (35 980–101 020)	72.3 (47.9–113.9)	110.3 (92.0–142.4)
1 664	1974–2015	53 820 (33 800–83 590)	61 910 (40 120–93 360)	75.4 (51.9–107.7)	114.1 (88.2–162.8)
2 772		53 820 (33 800–83 590)	59 840 (38 060–91 280)	73.0 (49.4–105.3)	110.0 (84.8–157.9)
3. Low *M*					
1 664	2006–2015	22 630 (14 540–35 440)	29 900 (19 150–47 160)	37.4 (24.6–56.3)	132.0 (113.7–153.3)
2 772		22 630 (14 540–35 440)	27 630 (16 860–44 910)	34.6 (21.7–53.6)	121.8 (103.7–142.5)
1 664	1974–2015	25 030 (16 080–38 870)	38 290 (24 280–58 220)	47.8 (30.9–71.1)	150.7 (112.1–220.6)
2 772		25 030 (16 080–38 870)	36 020 (22 020–55 960)	44.9 (28.1–68.3)	141.3 (104.0–209.6)
4. High *M*					
1 664	2006–2015	33 520 (21 970–53 480)	38 770 (25 820–61 790)	42.6 (29.3–64.1)	116.3 (100.7–134.1)
2 772		33 520 (21 970–53 480)	36 880 (23 890–59 920)	40.5 (27.1–62.2)	110.5 (95.6–128.3)
1 664	1974–2015	39 090 (24 390–64 020)	58 090 (34 850–95 340)	63.7 (38.8–102.3)	144.3 (100.6–239.6)
2 772		39 090 (24 390–64 020)	56 180 (32 940–93 440)	61.6 (36.7–100.3)	139.5 (96.7–233.5)

Table 12: Estimated projected probability of being below the target (40% B_0) or the soft or hard limits (20% or 10% B_0, respectively) for 2022 and 2026, for the base case and selected sensitivity models for west coast South Island hake, with assumptions of future recruitment either equal to the average over all years, or the most recent 10 years; and assuming future catch equals either current catch (1664 t) or the TACC (2772 t). YCS is year class strength.

Future catch (t)	Future YCS	P(>40%)	P(<20%)	P(<10%)
1. Base case				
1 664	2006–2015	0.51	0.00	0.00
2 772		0.39	0.00	0.00
1 664	1974–2015	0.93	0.00	0.00
2 772		0.89	0.00	0.00
2. Fixed 1984 YCS				
1 664	2006–2015	1.00	0.00	0.00
2 772		1.00	0.00	0.00
1 664	1974–2015	1.00	0.00	0.00
2 772		1.00	0.00	0.00
3. Low *M*				
1 664	2006–2015	0.37	0.00	0.00
2 772		0.26	0.01	0.00
1 664	1974–2015	0.80	0.00	0.00
2 772		0.70	0.00	0.00
4. High *M*				
1 664	2006–2015	0.63	0.00	0.00
2 772		0.53	0.00	0.00
1 664	1974–2015	0.97	0.00	0.00
2 772		0.95	0.00	0.00

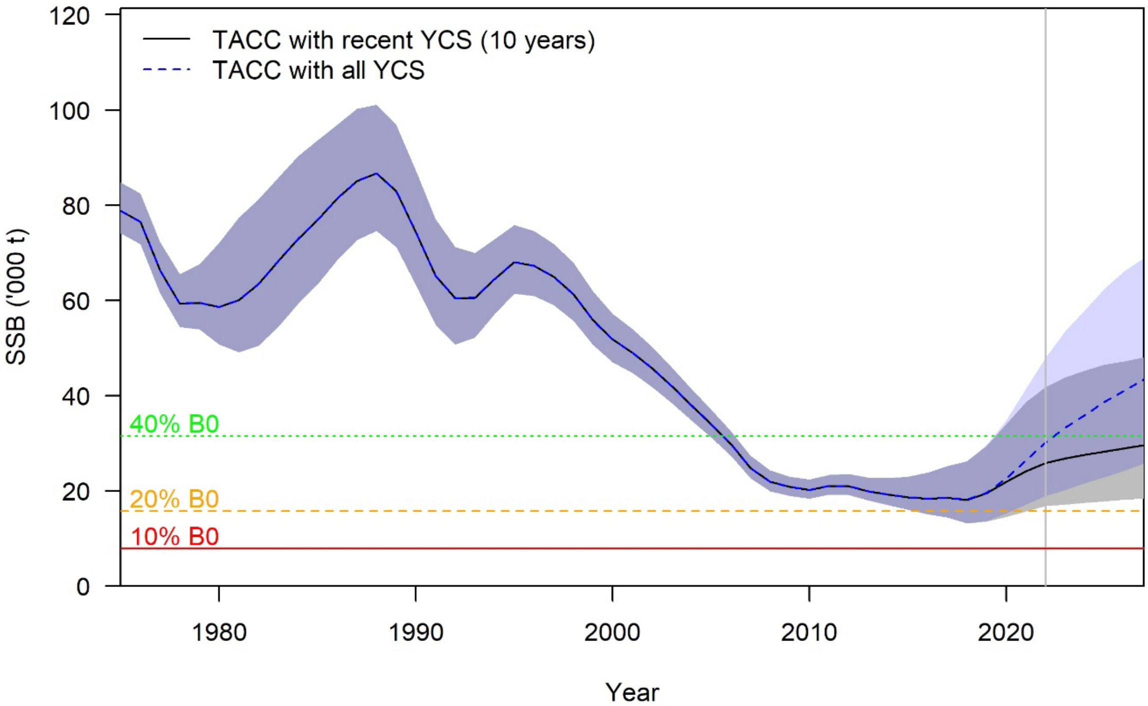

Figure 29: Posterior distribution of the historical (1975–2022, grey) and projected (2023–2027, purple) stock biomass for the base case model for west coast South Island hake. The solid line indicates the median trajectories, and the shaded areas indicate the 95% credible intervals. Horizontal lines indicate the target (green, 40% B_0), soft limit (yellow, 20% B_0), and hard limit (red, 10% B_0), respectively.

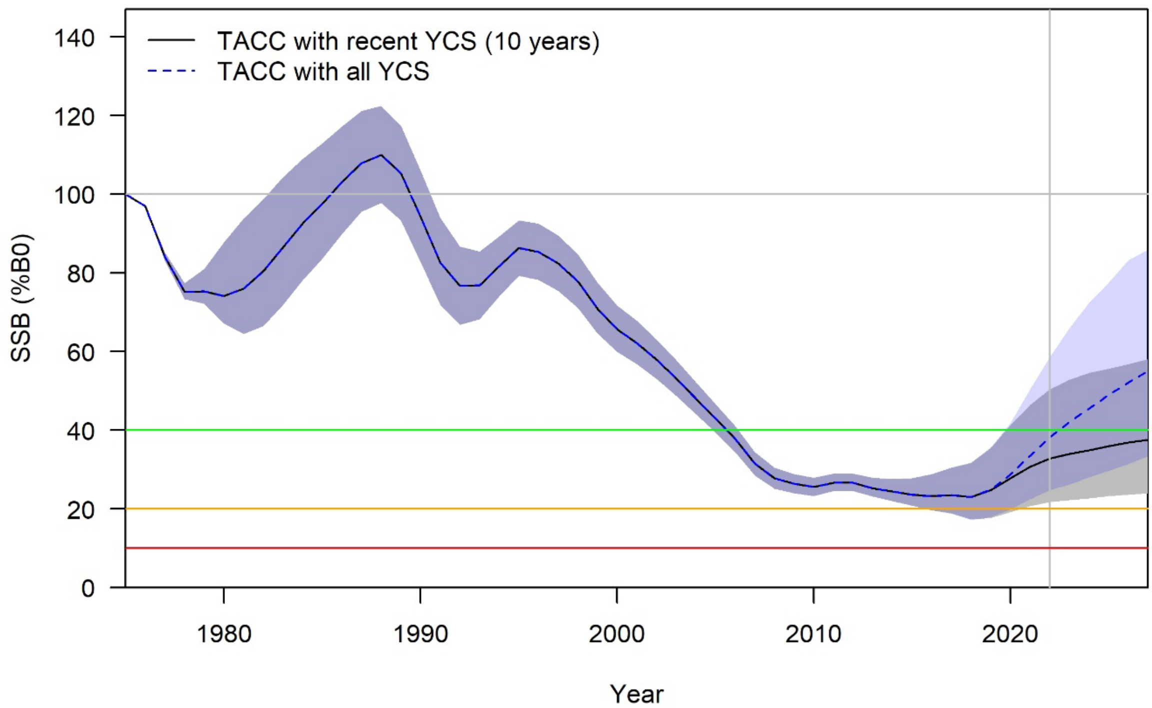

Figure 30: Posterior distribution of the historical (1975–2022, grey) and projected (2023–2027, purple) stock biomass as a percent of B_0 for the base case model for west coast South Island hake. The solid line indicates the median trajectories, and the shaded areas indicate the 95% credible intervals. Horizontal lines indicate the target (green, 40% B_0), soft limit (yellow, 20% B_0), and hard limit (red, 10% B_0), respectively.

3.6 Estimates of other population quantities

Typically, model outputs from stock assessments only consider the spawning stock (and occasionally vulnerable biomass quantities and trajectories). However, model output quantities can also include a wider range of alternative reference values that may be useful for a more complete understanding of the changes in a stock over time. The base case model is used here to compare trajectories over the history of the fishery in terms of total population numbers (abundance), as well as the biomass of immature fish to complement the information on changes in spawning stock biomass.

Figure 31 shows the trajectory from the base case model of the total number of 1+ aged fish in the population over the period 1975–2022. This suggests that the current number of fish in the population is at about 69% (95% credible interval 62–78%) of the initial total abundance. Figure 32 shows the biomass trajectory of the immature 1+ aged biomass from the population over the period 1975–2022. This suggests that the current biomass of immature fish in the population is at about 87% (95% credible interval 82–92%) of the initial total biomass of immature fish.

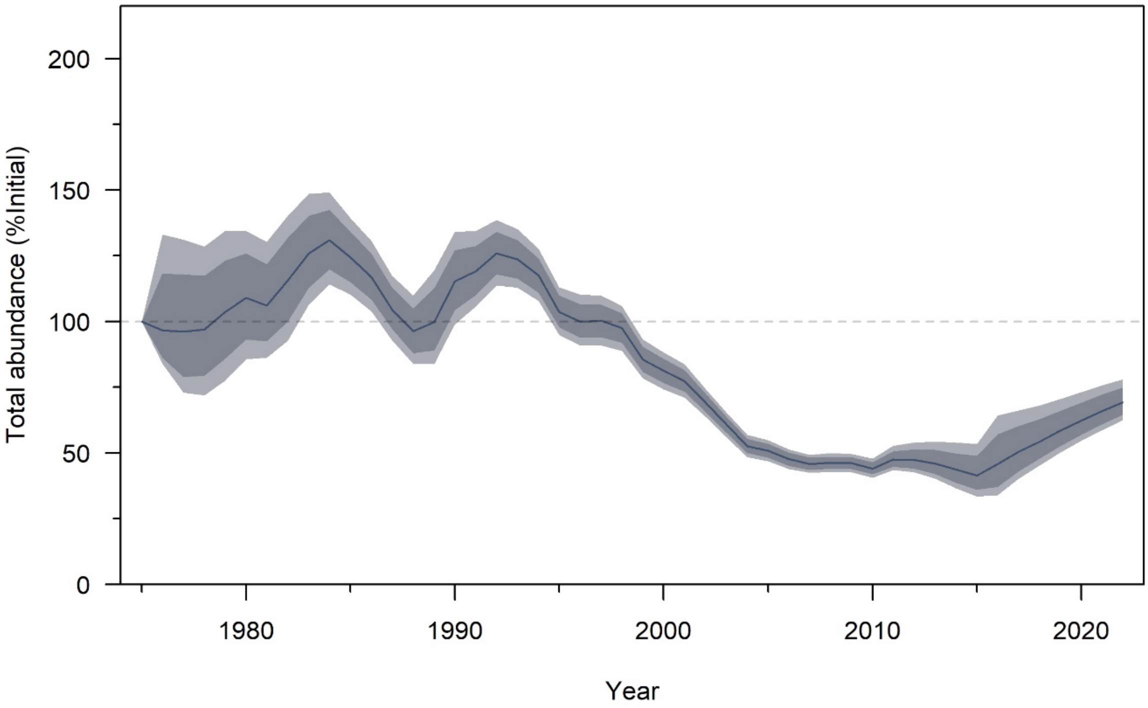

Figure 31: The base case model posterior distribution of the total abundance (number) of immature and mature hake (%Initial) for 1975–2022. The blue line indicates the trajectory of the initial total abundance, the dark shaded area indicates the 80% credible interval, and the light shaded area indicates the 95% credible interval.

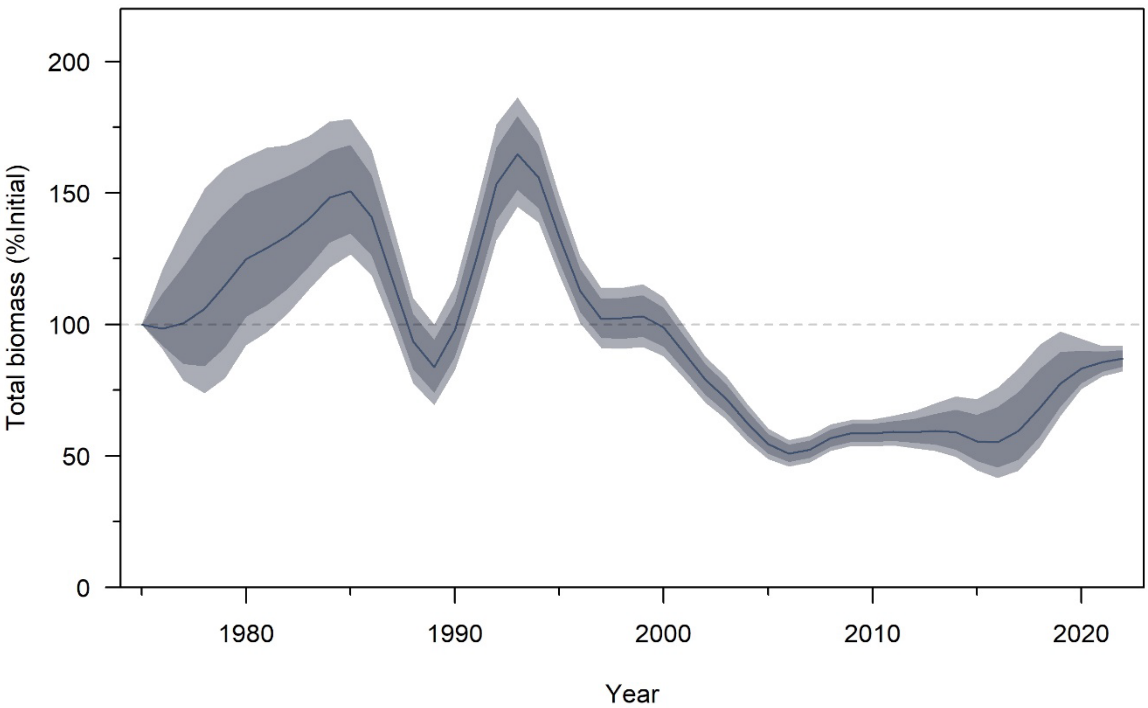

Figure 32: The base case model posterior distribution of the total biomass of immature hake (%Initial) for 1975–2022. The blue line indicates the trajectory of the initial total abundance, the dark shaded area indicates the 80% credible interval, and the light shaded area indicates the 95% credible interval.

4. DISCUSSION

The initial stock assessment model for west coast South Island hake in HAK 7 presented here was developed from the 2019 assessment (Kienzle et al. 2019). The stock assessment by Kienzle et al. (2019) concluded that the spawning stock had been reduced to a low point between 2016 and 2019, and that at the then current catch levels (about 1400 t) the stock was likely to fluctuate around that level.

This assessment updated the previous model with new observations made since the previous assessment, revised the annual cycle, updated the survey indices, and used the 5+ age frequencies as observations. This assessment suggested that the stock catch was lower than projected and that the stock was likely to have increased since the last assessment and is either rebuilding towards the target biomass or may have already rebuilt.

The 2021 plenary for west coast South Island hake (Fisheries New Zealand 2021) noted a number of major sources of uncertainty in previous assessments. That report noted that the *Tangaroa* survey had shown a decline over time. With the new (2021) biomass estimate at a level similar to the index in 2012, the decline estimated by this assessment from about 2016 was not quite as strong as was estimated in the previous assessment. However, the time series for the stock is short and the two year gap between surveys increases the uncertainty of the level that the stock may have rebuilt to.

The assumption that the west coast South Island stock (including Puysegur Bank) is a single stock remains an uncertainty—specifically the stock affinity of hake in the Puysegur Bank area. However, as noted in the plenary (Fisheries New Zealand 2023), the association of Puysegur hake with the west coast South Island is the most parsimonious interpretation of available information.

Assessment model sensitivities did not suggest that alternative assumptions would lead to a significantly different outcome, and MCMC diagnostics were reasonable for almost all estimated parameters. Model projections at the level of the current catch suggested that the biomass of hake off the west coast South Island would continue to increase, and projections with recent (lower) year class strengths at a level of the TACC for HAK 7 would indicate a slower increase towards the target biomass of 40% B_0 over the next five years.

Preliminary models that used the observations from the survey biomass split into juveniles and adults, and the age frequencies into juveniles and adults (i.e., by considering juveniles as males < 65 cm and females < 69 cm) were also developed. Investigations showed that these models provided little information on year class strengths and gave similar prognosis as the models presented here. We note that this approach could be developed for the next assessment (due in 2025), as the additional survey and commercial catch-at-age data may contain information on the year class progression from the juveniles into the adult population.

5. MANAGEMENT IMPLICATIONS

Reference points for hake off the west coast South Island include the default management target of 40% B_0, a soft limit of 20% B_0, and a hard limit of 10% B_0. The overfishing threshold was assumed to be $F_{40\%B_0}$, calculated as 0.18 using the base case model with recent year class strengths using the CAY calculation method of CASAL (Bull et al. 2012). B_{2022} was estimated to be virtually certain to be above the target for all sensitivity runs and exceptionally unlikely to be below the soft or hard limit. Overfishing is exceptionally unlikely to be occurring (Figure 33).

Based on the four projections carried out, the stock status is unlikely to change over the next five years at recent catch levels and therefore overfishing is exceptionally unlikely to manifest.

The estimates of additional, unreported fishing mortality of 5% before the introduction of the QMS and 2% thereafter are plausible, but highly uncertain. The inclusion of the additional mortality estimates did not significantly change the conclusions of the model or the management implications.

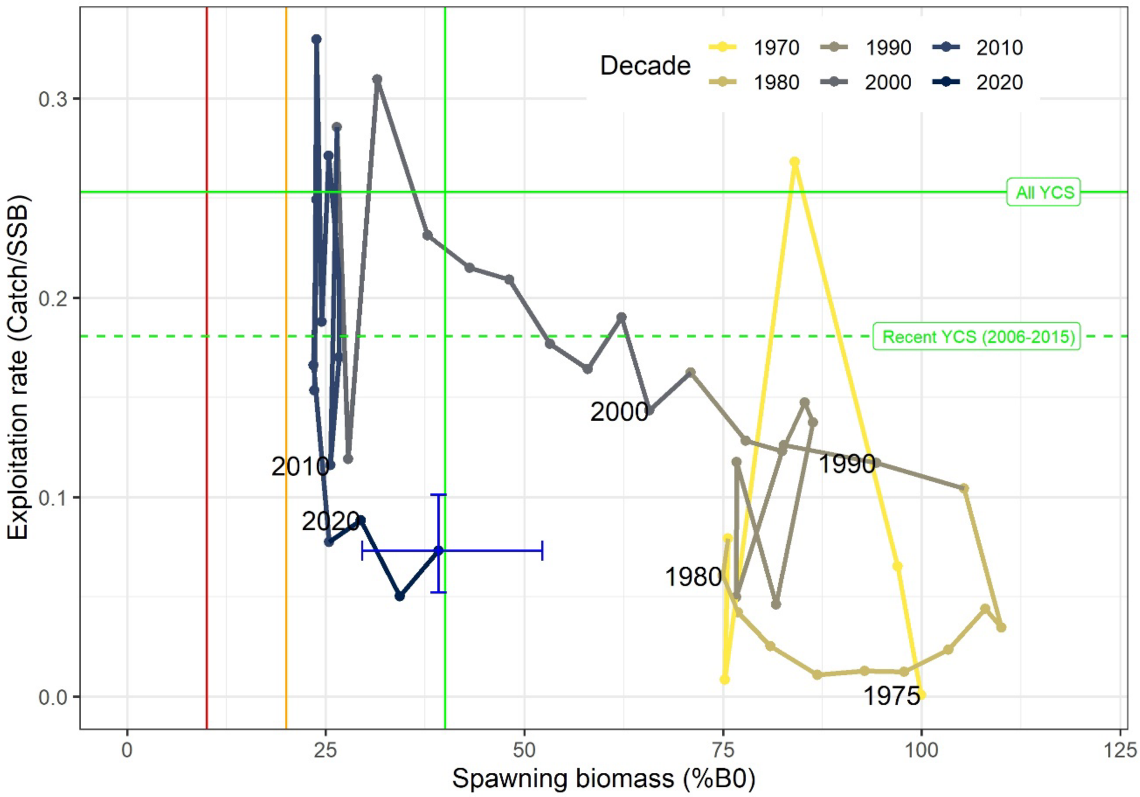

Figure 33: Trajectory over time of exploitation rate (*U*) and spawning biomass (% B_0), for the base case model from the start of the assessment period in 1975, to 2022 (in blue). The red vertical line at 10% B_0 represents the hard limit, the yellow line at 20% B_0 is the soft limit, and green lines are the % B_0 target (40% B_0) and the corresponding exploitation rate (U_{40} = 0.25 for all YCS and U_{40} = 0.18 for recent YCS) calculated using CASAL CAY calculation. Biomass and exploitation rate estimates are medians from MCMC results. The blue cross represents the limits of the 95% credible intervals of estimated the ratio of the *SSB* to B_0 and exploitation rate in 2022.

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7. REFERENCES

Anderson, O.F.; Edwards, C.T.T.; Ballara, S. (2019). Non-target fish and invertebrate catch and discards in New Zealand hoki, hake, ling, silver warehou, and white warehou trawl fisheries from 1990–91 to 2016–17. *New Zealand Aquatic Environment and Biodiversity Report No. 220*. 121 p.

Ballara, S.L. (2018). Descriptive analysis of the fishery for hake (*Merluccius australis*) in HAK 1, 4 and 7 from 1989–90 to 2014–15, and a catch-per-unit-effort (CPUE) analysis for Chatham Rise and WCSI hake. *New Zealand Fisheries Assessment Report 2018/55*. 57 p.

Ballara, S.L.; O'Driscoll, R.L.; Saunders, R.J. (2022). Catch-at-age for hake (*Merluccius australis*) and ling (*Genypterus blacodes*) for the 2020–21 fishing year and from research trawl surveys in 2021–22, and a summary of the available data sets from the New Zealand EEZ. *New Zealand Fisheries Assessment Report 2022/56*. 94 p.

Bull, B.; Dunn, A.; McKenzie, A.; Gilbert, D.J.; Smith, M.H.; Bian, R.; Fu, D. (2012). CASAL (C++ algorithmic stock assessment laboratory) User Manual v2.30-2012/03/21. *NIWA Technical Report 135*. 280 p.

Chapman, D.G.; Robson, D.S. (1960). The analysis of a catch curve. *Biometrics 16*: 354–368.

Colman, J.A. (1997). Stock assessment of hake (*Merluccius australis*) for the 1997–98 fishing year. New Zealand Fisheries Assessment Research Document 97/19. (Unpublished report held by NIWA library, Wellington.) 15 p.

Colman, J.A.; Stocker, M.; Pikitch, E. (1991). Assessment of hake (*Merluccius australis*) stocks for the 1991–92 fishing year. New Zealand Fisheries Assessment Research Document 91/14. (Unpublished report held by NIWA library, Wellington.) 29 p.

Colman, J.A.; Vignaux, M. (1992). Assessment of New Zealand hake (*Merluccius australis*) stocks for the 1992–93 fishing year. New Zealand Fisheries Assessment Research Document 92/17. (Unpublished report held by NIWA library, Wellington.) 23 p.

Devine, J.A.; Stevens, D.W.; Ballara, S.L. (2022). Trawl survey for middle depth fish species off the west coast South Island, July–August 2021 (TAN2107). *New Zealand Fisheries Assessment Report 2022/53*. 131 p.

Dunn, A. (1998). Stock assessment of hake (*Merluccius australis*) for the 1998–99 fishing year. New Zealand Fisheries Assessment Research Document 98/30. (Unpublished report held by NIWA library, Wellington.) 19 p.

Dunn, A. (2001). Stock assessment of hake (*Merluccius australis*) for the 2000–01 fishing year. *New Zealand Fisheries Assessment Report 2001/22*. 31 p.

Dunn, A. (2003a). Stock assessment of hake (*Merluccius australis*) for the 2002–03 fishing year. *New Zealand Fisheries Assessment Report 2003/38*. 57 p.

Dunn, A. (2003b). Revised estimates of landings of hake (*Merluccius australis*) for the west coast South Island, Chatham Rise, and Sub-Antarctic stocks in the fishing years 1989–90 to 2000–01. *New Zealand Fisheries Assessment Report 2003/39*. 36 p.

Dunn, A. (2004). Stock assessment of hake (*Merluccius australis*) for the 2003–04 fishing year. *New Zealand Fisheries Assessment Report 2004/34.* 62 p.

Dunn, A. (2006). Stock assessment of hake (*Merluccius australis*) in HAK 1 & 4 for the 2005–06 fishing year. (Final Research Report for Ministry of Fisheries Project HAK2003-01 held by Fisheries New Zealand.) 47 p.

Dunn, A.; Ballara, S.L.; Phillips, N.L. (2006). Stock assessment of hake (*Merluccius australis*) in HAK 1 & 4 for the 2004–05 fishing year. *New Zealand Fisheries Assessment Report 2006/11*. 63 p.

Dunn, A.; Horn, P.L.; Cordue, P.L.; Kendrick, T.H. (2000). Stock assessment of hake (*Merluccius australis*) for the 1999–2000 fishing year. *New Zealand Fisheries Assessment Report 2000/50*. 50 p.

Dunn, A.; Mormede, S.; Webber, D.N. (2021a). Stock assessment of hake (*Merluccius australis*) in the Sub-Antarctic (HAK 1) for the 2020–21 fishing year. *New Zealand Fisheries Assessment Report 2021/75*. 37 p.

Dunn, A.; Mormede, S.; Webber, D.N. (2021b). Descriptive analysis and stock assessment model inputs of hake (*Merluccius australis*) in the Sub-Antarctic (HAK 1) for the 2020–21 fishing year. New Zealand Fisheries Assessment Research Document 2021/74. (Unpublished report held by NIWA library, Wellington.) 52 p.

Dunn, A.; Mormede, S.; Webber, D.N. (2023). Descriptive analysis and model inputs for the 2022 stock assessment of hake (*Merluccius australis*) off the west coast South Island (HAK 7), to the 2020–21 fishing year. *New Zealand Fisheries Assessment Report 2023/44*. 56 p.

Dunn, M.R. (2019). Stock assessment of Sub-Antarctic hake (part of HAK 1) for 2018. *New Zealand Fisheries Assessment Report 2019/52*. 33 p.

Finucci, B. (2019). Descriptive analysis and a catch-per-unit-effort (CPUE) analysis of the West Coast South Island (HAK 7) fishery for hake (*Merluccius australis*). *New Zealand Fisheries Assessment Report 2019/55*. 49 p.

Fisheries New Zealand (2021). *Report from the Fishery Assessment Plenary, May 2021: stock assessments and stock status*. Compiled by the Fisheries Science Team, Fisheries New Zealand. Ministry for Primary Industries, 1782 p.

Fisheries New Zealand (2023). *Report from the Fishery Assessment Plenary, May 2023: stock assessments and stock status*. Compiled by the Fisheries Science Team, Fisheries New Zealand. Ministry for Primary Industries, 1904 p.

Francis, R.I.C.C. (2011). Data weighting in statistical fisheries stock assessment models. *Canadian Journal of Fisheries and Aquatic Sciences 68*: 1124–1138.

Gelman, A.B.; Carlin, J.S.; Stern, H.S.; Rubin, D.B. (1995). *Bayesian data analysis*. Chapman and Hall.

Geweke, J. (1992). Evaluating the accuracy of sampling-based approaches to calculating posterior moments. *In*: Bernardo, J.M., Berger, J.O., Dawid, A.P., Smith, A.F.M. (Eds.), pp. 169–194. *Bayesian Statistics, 4*. Clarendon Press.

Gilks, W.R.; Richardson, S.; Spiegelhalter, D.J. (1998). *Markov Chain Monte Carlo in practice*. CRC Interdisciplinary Statistics. Chapman & Hall.

Heidelberger, P.; Welch, P. (1983). Simulation run length control in the presence of an initial transient. *Operations Research 31*: 1109–1144.

Hoenig, J.M. (1983). Empirical use of longevity data to estimate mortality rates. *Fisheries Bulletin 81*: 899–903.

Holmes, S.J. (2021). Stock assessment of hake (*Merluccius australis*) on Chatham Rise for the 2019-20 fishing year. *New Zealand Fisheries Assessment Report 2021/22*. 55 p.

Horn, P.L. (1997). An ageing methodology, growth parameters, and estimates of mortality for hake (*Merluccius australis*) from around the South Island, New Zealand. *Marine and Freshwater Research 48*: 201–209.

Horn, P.L. (2008). Stock assessment of hake (*Merluccius australis*) in the Sub-Antarctic for the 2007–08 fishing year. *New Zealand Fisheries Assessment Report 2008/49*. 66 p.

Horn, P.L. (2011). Stock assessment of hake (*Merluccius australis*) off the west coast of South Island (HAK 7) for the 2010–11 fishing year. *New Zealand Fisheries Assessment Report 2011/33*. 46p.

Horn, P.L. (2013a). Stock assessment of hake (*Merluccius australis*) in the Sub-Antarctic (part of HAK 1) for the 2011–12 fishing year. *New Zealand Fisheries Assessment Report 2013/5*. 52 p.

Horn, P.L. (2013b). Stock assessment of hake (*Merluccius australis*) on the Chatham Rise (HAK 4) and off the west coast of South Island (HAK 7) for the 2012–13 fishing year. *New Zealand Fisheries Assessment Report 2013/31*. 58 p.

Horn, P.L. (2015). Stock assessment of hake (*Merluccius australis*) in the Sub-Antarctic (part of HAK 1) for the 2014–15 fishing year. *New Zealand Fisheries Assessment Report 2015/29*. 55 p.

Horn, P.L. (2017). Stock assessment of hake (*Merluccius australis*) on the Chatham Rise (HAK 4) and off the west coast of South Island (HAK 7) for the 2016-17 fishing year. *New Zealand Fisheries Assessment Report 2017/47*. 70 p.

Horn, P.L.; Ballara, S.L. (2018). A comparison of a trawl survey index with CPUE series for hake (*Merluccius australis*) off the west coast of South Island (HAK 7). *New Zealand Fisheries Assessment Report 2018/13*. 54 p.

Horn, P.L.; Dunn, A. (2007). Stock assessment of hake (*Merluccius australis*) on the Chatham Rise for the 2006–07 fishing year. *New Zealand Fisheries Assessment Report 2007/44*. 62 p.

Horn, P.L.; Francis, R.I.C.C. (2010). Stock assessment of hake (*Merluccius australis*) on the Chatham Rise for the 2009–10 fishing year. *New Zealand Fisheries Assessment Report 2010/14*. 65 p.

Hurst, R.J.; Bagley, N.W.; Anderson, O.F.; Francis, M.P.; Griggs, L.H.; Clark, M.R.; Paul, L.J.; Taylor, P.R. (2000). Atlas of juvenile and adult fish and squid distributions from bottom and midwater trawls and tuna longlines in New Zealand waters. *NIWA Technical Report 84*. 162 p.

Kienzle, M.; McGregor, V.; Dunn, M.R. (2019). Stock assessment of hake (*Merluccius australis*) on the west coast of South Island (HAK 7) for the 2018–19 fishing year. *New Zealand Fisheries Assessment Report 2019/66*. 47 p.

MacGibbon, D.J. (2019). Inshore trawl survey of the west coast South Island and Tasman and Golden Bays, March-April 2019 (KAH1902). *New Zealand Fisheries Assessment Report 2019/64*. 87 p.

MacGibbon, D.J.; Walsh, C.; Buckthought, D.; Bian, R. (2022). Inshore trawl survey off the west coast South Island and in Tasman Bay and Golden Bay, March–April 2021 (KAH2103). *New Zealand Fisheries Assessment Report 2022/11*. 97 p.

O'Driscoll, R.L.; Ballara, S.L. (2018). Trawl survey of middle depth fish abundance on the west coast South Island, August 2016 (TAN1609). *New Zealand Fisheries Assessment Report 2018/47*. 74 p.

O'Driscoll, R.L.; Ballara, S.L. (2019). Trawl survey of middle depth fish abundance on the west coast South Island, July-August 2018 (TAN1807). *New Zealand Fisheries Assessment Report 2019/19*. 120 p.

Ricker, W.E. (1975). Computation and interpretation of biological statistics of fish populations. *Bulletin of the Fisheries Research Board of Canada 191*: 29–73.

Saunders, R.; Hart, A.C.; Horn, P.L.; Sutton, C.P. (2021). Catch-at-age for hake (*Merluccius australis*) and ling (*Genypterus blacodes*) for the 2018–19 fishing year and from a research trawl survey in 2020, and a summary of the available data sets from the New Zealand EEZ. *New Zealand Fisheries Assessment Report 2021/15*. 97 p.

8. APPENDIX A: MPD SUMMARY TABLES

Table A.1: MPD objective function values for the base case and sensitivity models.

Component	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
KAH biomass	–	–	–	–	–	–	59.3	–	–	–	–	–	–	–	–
TAN Biomass	0.3	3.8	-0.4	1.1	0.3	0.5	1.7	0.1	-2.4	0.6	-0.3	0.3	-3.5	5.9	0.3
Deep fishery AFs	673.2	659.3	682.0	663.9	670.7	674.3	676.6	675.6	669.9	677.6	667.1	673.4	673.2	673.3	673.2
North shallow AFs	829.2	779.4	830.9	820.6	821.7	826.4	834.1	831.2	823.5	813.0	801.4	829.5	827.6	828.5	829.2
South shallow AFs	–	–	–	–	–	–	–	–	–	254.9	253.9	–	–	–	–
South shallow AFs (<2007)	485.5	476.5	481.3	483.1	483.2	477.0	483.9	484.8	484.5	–	–	485.4	483.6	485.6	485.5
South shallow AFs (2007+)	–	–	–	–	–	–	–	–	–	285.5	285.7	–	–	–	–
TAN AFs	148.9	130.0	147.6	151.2	147.1	154.6	151.0	122.6	140.1	149.2	149.1	149.1	150.0	148.8	148.9
KAH LFs	–	–	–	–	–	–	78.8	–	–	–	–	–	–	–	–
Prior B0	11.3	11.3	11.3	11.4	11.3	11.3	11.2	11.3	11.3	11.3	11.2	11.3	11.3	11.3	11.3
Prior natural mortality (average)	–	–	–	–	–	–	–	–	–	–	0.0	–	–	–	–
Prior natural mortality (difference)	–	–	–	–	–	–	–	–	–	–	2.5	–	–	–	–
Prior KAH q	–	–	–	–	–	–	0.0	–	–	–	–	–	–	–	–
Prior TAN q	-2.8	-2.7	-2.9	-2.6	-2.8	-2.8	-2.8	-2.8	-2.9	-2.7	-2.9	-2.8	-2.8	-2.8	-2.7
Prior YCS	-15.4	-13.6	-16.4	-13.7	-15.3	-15.8	-7.8	-15.3	-14.7	-15.5	-16.1	-15.9	-15.2	-15.6	-15.4
Prior KAH cv process error	–	–	–	–	–	–	-6.9	–	–	–	–	–	–	–	–
Prior TAN cv process error	-6.9	-6.9	-6.9	-6.9	-6.9	-6.9	-6.9	-6.9	-6.9	-6.9	-6.9	-6.9	–	–	-6.9
Prior selectivity deep female	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Prior selectivity deep male	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Prior selectivity north shallow female	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Prior selectivity north shallow male	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Prior selectivity south shallow female	–	–	–	–	–	–	–	–	–	0.0	0.0	–	–	–	–
Prior selectivity south shallow male	–	–	–	–	–	–	–	–	–	0.0	0.0	–	–	–	–
Prior selectivity south shallow <2007 female	–	–	–	–	–	–	–	–	–	0.0	0.0	–	–	–	–
Prior selectivity south shallow <2007 male	–	–	–	–	–	–	–	–	–	0.0	0.0	–	–	–	–
Prior selectivity south shallow 2007+ female	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	–	–	0.0	0.0	0.0	0.0
Prior selectivity south shallow 2007+ male	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	–	–	0.0	0.0	0.0	0.0
Prior KAH selectivity	–	–	–	–	–	–	0.0	–	–	–	–	–	–	–	–
Prior TAN selectivity female	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Prior TAN selectivity male	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
YCS penalty	9.0	7.7	9.6	7.5	8.9	9.3	6.4	8.9	8.5	9.0	9.4	9.3	8.9	9.1	9.0
Total objective function	2 132	2 045	2 136	2 115	2 118	2 128	2 278	2 109	2 111	2 176	2 154	2 133	2 133	2 144	2 132