Fisheries New Zealand

Tini a Tangaroa

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

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

ISSN 1179-5352 (online)
ISBN 978-1-99-101989-9 (online)

November 2021

New Zealand Government

Requests for further copies should be directed to:

Publications Logistics Officer
Ministry for Primary Industries
PO Box 2526
WELLINGTON 6140

Email: brand@mpi.govt.nz
Telephone: 0800 00 83 33
Facsimile: 04-894 0300

This publication is also available on the Ministry for Primary Industries websites at:
http://www.mpi.govt.nz/news-and-resources/publications
http://fs.fish.govt.nz go to Document library/Research reports

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Dunn, A.[1]; Mormede, S.[2]; Webber, D.N.[3] (2021). 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.**

Hake (*Merluccius australis*) are 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 Sub-Antarctic stock (hake in HAK 1 south of about 46° S) up to the end of the 2020–21 fishing year. The main indices of abundance provided to the model were the Sub-Antarctic summer and autumn trawl surveys and associated age frequency data. The biomass indices provided the most information to the model. This assessment updated the previous model with new observations made since the last assessment, revised the annual cycle and catch-per-unit-effort (CPUE) indices, and corrected the time series of the November biomass indices. These changes to the previous survey indices and the new observations suggested that recent year classes were not as weak as had previously been estimated and that current status was consequently slightly higher.

The median of the posterior distribution of initial biomass was 59 000 t (95% credible intervals 43 220–93 600) with current status of 62% B_0 (95% credible intervals 49–75% 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 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 in the Sub-Antarctic would remain relatively stable, and only projections with recent (lower) year class strengths at a catch level of the Total Allowable Commercial Catch for HAK 1 would result in a decline, albeit slowly, towards the target biomass of 40% B_0 over the next five years.

[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*) are 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 250–800 m (Hurst et al. 2000). Hake are caught mainly by deepwater trawlers typically as bycatch in hoki (*Macruronus novaezelandiae*) target fisheries and with some caught by direct targeting (Ballara 2018, Dunn et al. 2021).

The current management of hake divides the fishery into 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). An administrative Fishstock (with no recorded landings) is also defined for the Kermadec FMA (HAK 10) (Fisheries New Zealand 2020). However, there are likely to be three main biological stocks of hake. These are the west coast of the South Island (WCSI, HAK 7), the Chatham Rise (HAK 4 and the northern regions in HAK 1), and the Sub-Antarctic (HAK 1) (Fisheries New Zealand 2020).

The length frequencies of hake were different between the west coast and both the Chatham Rise and Sub-Antarctic. The growth parameters were also different between the three areas (Horn 1997) and juvenile hake are 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 to those off the east coast of the North Island, but significant differences between these hake and those from the Sub-Antarctic, Puysegur Bank, and off the west coast of the South Island. Hake in the Puysegur Bank area were similar to those from off the west coast South Island, but not always different from the Sub-Antarctic hake. Hence, the stock affinity of hake from Puysegur Bank was considered uncertain (Kienzle et al. 2019).

Hake stocks have previously been assessed with assessments on at least one of the three stocks each year since 1991. Previous assessments of hake include 1991–92 (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), and 2019–20 (Holmes 2021).

Sub-Antarctic hake stock assessments have typically been implemented as single area integrated statistical catch-at-age models using commercial catch-at-age frequency, CPUE, resource survey biomass, and survey age frequency observations. The Bayesian stock assessment software CASAL (Bull et al. 2012) has been used for all assessments since 2002–03, and the most recent assessments were Holmes (2021) for the Chatham Rise, Dunn (2019) for the Sub-Antarctic, and Kienzle et al. (2019) for the WCSI. The most recent characterisation and CPUE index was recently updated by Dunn et al. (2021), including data up to the end of the 2019–20 fishing year.

The stock assessment by Dunn (2019) concluded that the Sub-Antarctic spawning stock had been reduced to 50% of the pre-exploitation biomass (B_0), above the management target of 40% B_0, and that at current catch levels (about 1400 t) the stock was likely to fluctuate around current levels. However, the assessment noted that recruitment since 2008 had been lower than average and that increased catches would likely reduce the stock size.

The 2020 plenary for Sub-Antarctic hake (Fisheries New Zealand 2020) noted a number of major sources of uncertainty in the assessment for Sub-Antarctic hake: the summer trawl survey series has shown a decline over time, but individual survey estimates are variable, and catchability clearly varies between surveys. The general lack of contrast in this series (the main relative abundance series) makes it difficult to accurately estimate past and current biomass; the assumption of a single Sub-Antarctic stock (including the Puysegur Bank), independent of hake in all other areas, is the most parsimonious interpretation of available information. However, this assumption may not be correct: uncertainty about the size of recent year classes affects the reliability of stock projections; there are patterns in the residuals in the commercial catch-at-age data fitted by the mode; although the catch history used in the assessment has been corrected for some misreported catch, it is possible that additional misreporting exists.

Further, the 2020 plenary (Fisheries New Zealand 2020) noted that the assessment by Dunn (2019) had incorrectly applied the 'core area' (300–800 m) biomass estimates from the trawl survey of Sub-Antarctic hake rather than 'core + Puysegur' (300–800 m plus the 800–1000 m depth strata in the Puysegur Bank area) values for the 2013 and 2017 years, and that this was likely to have "…resulted in a slightly more pessimistic assessment".

This report updates the Sub-Antarctic hake stock assessment with the most recent data (Dunn et al. 2021, Saunders et al. 2021) 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. (2021), and the age frequency data by Saunders et al. (2021). This report fulfils Specific Objective 1 of Project HAK2020-01. The overall Objective was "To carry out stock assessments of hake (*Merluccius australis*) in the Sub-Antarctic (HAK 1) including estimating stock biomass and stock status" and Specific Objective 2 was "To update the stock assessment of the Sub-Antarctic 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".

2. METHODS

2.1 Data available for the assessment

2.1.1 Catch history

In the late 1990s and early 2000, fishers were found to have misreported hake catches between Quota Management Areas (QMAs). The reported catches of hake in each area were reviewed in 2002 and likely misreported records identified by Dunn (2003b), who then provided revised estimates of the total landings by stock. Almost all the area misreporting was from HAK 7 (WCSI) to the Chatham Rise (HAK 4 and the part of HAK 1 on the Chatham Rise), with only a small amount to 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 was no evidence of similar area misreporting since 2001–02 (Ballara 2018).

Because a substantial proportion of hake catch was taken in the September months of the early years (Figure 1) when catch and effort data were available for the fishery (1990–1994), and this proportion was more likely to be similar in characteristics to the catch taken in October–December (the period of the year when more than three quarters of the catch was taken), catch and effort from September was assigned to the following fishing year. A revised catch history for hake, accounting for this misreporting, and also with the September catch allocated to the following fishing year (and labelled model year, 1 September to 31 August, in this report), for each stock is given in Table 1 and shown in Figure 2. The total catch for 2021 was not known at the time of writing this report and was assumed to be equal to the average catch reported over the most recent five years.

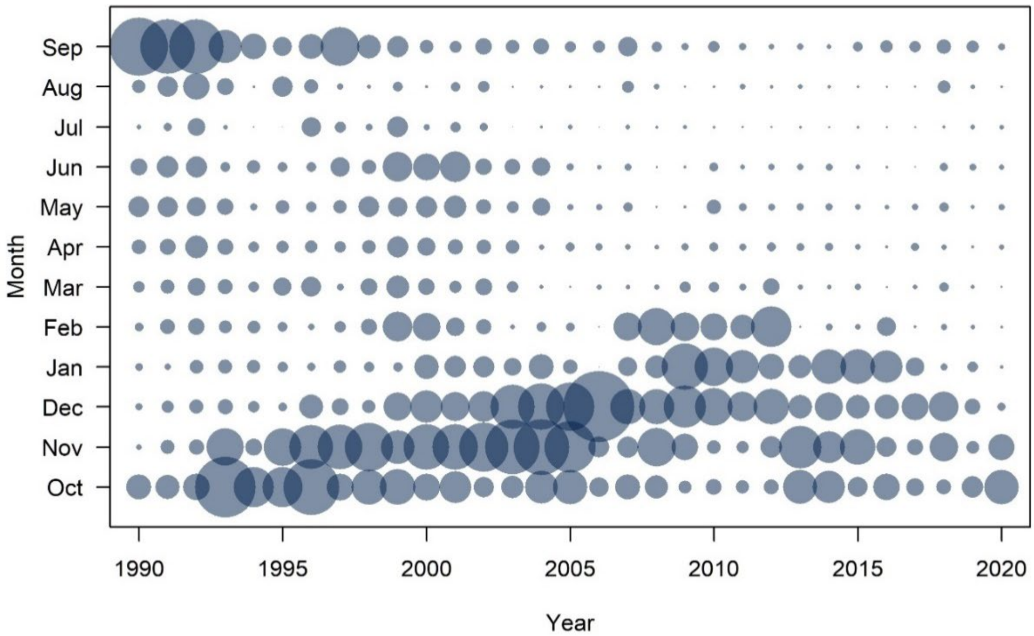


Figure 1: Relative catch of hake in the Sub-Antarctic by month and calendar year, 1990–2020.

Table 1: Total (scaled) catches (t) by stock for hake from 1990 to 2020 for (left columns) the October–September definition of a fishing year (where 1990 is 1 October 1989–30 September 1990), and (right column) September–August model year (where 1990 is 1 September 1989–31 August 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. (Continued on next page)

	Oct-Sep fishing year					Sep-Aug model year
Year	Chatham Rise	Sub-Antarctic	WCSI	Not assigned	Total	Sub-Antarctic
1990	1 015	1 827	4 903	39	7 784	718
1991	963	2 366	6 147	73	9 549	2 318
1992	2 420	2 749	3 026	1	8 196	2 806
1993	2 801	3 265	7 121	37	13 225	3 919
1994	2 952	1 452	2 958	2	7 364	1 620
1995	4 097	1 844	8 839	9	14 789	1 982
1996	4 535	2 888	8 662	46	16 131	2 789
1997	4 790	2 274	6 111	48	13 222	1 919
1998	4 691	2 601	7 404	59	14 755	2 944
1999	4 381	2 792	8 159	6	15 338	2 871
2000	3 691	3 011	6 895	2	13 600	3 100
2001	2 965	2 787	8 357	7	14 117	2 816
2002	1 785	2 510	7 519	0	11 813	2 444
2003	1 407	2 741	7 432	1	11 581	2 780
2004	2 492	3 251	7 943	0	13 686	3 228
2005	3 532	2 530	7 314	0	13 377	2 591
2006	494	2 555	6 905	0	9 955	2 538
2007	1 112	1 812	7 668	2	10 594	1 706
2008	1 109	2 204	2 617	0	5 930	2 330
2009	1 845	2 427	5 953	1	10 226	2 445
2010	412	1 958	2 346	0	4 716	1 927
2011	975	1 288	3 574	1	5 838	1 319
2012	216	1 893	4 459	0	6 568	1 902
2013	373	1 883	5 434	1	7 690	1 878
2014	219	1 832	3 641	0	5 693	1 840
2015	390	1 639	6 219	0	8 248	1 608
2016	355	1 504	2 863	1	4 722	1 470
2017	406	1 037	4 701	1	6 145	1 042

Year	Chatham Rise	Sub-Antarctic	WCSI	Not assigned	Total	Sub-Antarctic
	Oct-Sep fishing year					Sep-Aug model year
2018	412	1 205	3 085	1	4 704	1 175
2019	443	636	1 562	0	2 642	662
2020	266	930	2 062	4	3 262	983
Total	57 546	65 691	171 880	344	295 460	65 670

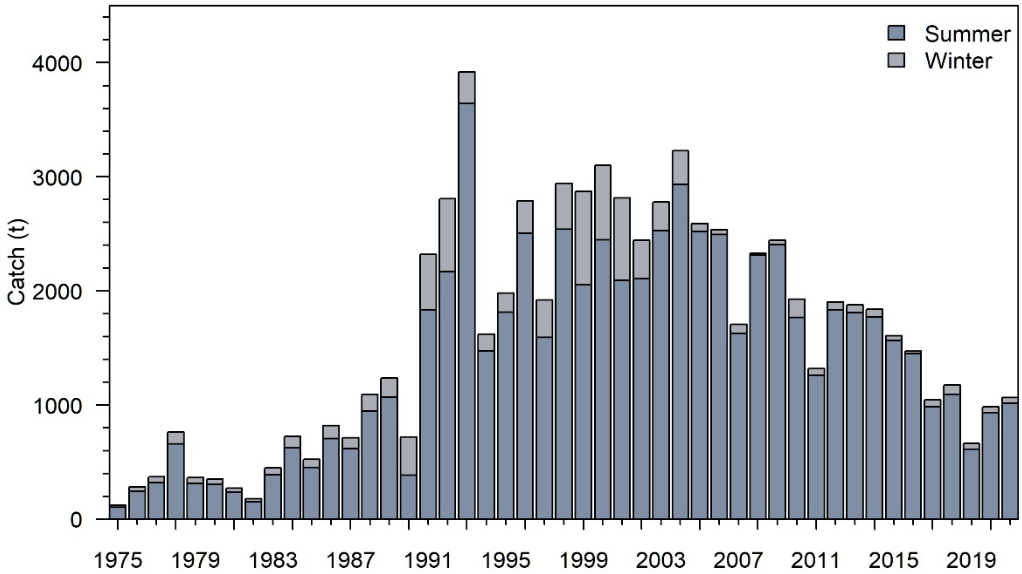


Figure 2: Annual reported catch of Sub-Antarctic hake (summer and winter) for the model years 1974–75 to 2019–20.

2.1.2 Biological parameters

Revised length-weight and growth curve parameters were described by Dunn et al. (2021), using all available data. Revised length-weight parameters and Bayesian von Bertalanffy growth curves are given in Table 2. However, the difference these and the parameters for the length weight (Horn 2013a) and growth (Horn 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 Ricker (1975), Hoenig (1983), and Chapman & Robson (1960). 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 Sub-Antarctic hake.

Relationship	Reference	Parameter (units)	Value Both	Male	Female
Natural mortality[1]	(Horn & Francis 2010)	M (y^{-1})		0.19	0.19
von Bertalanffy growth	(Dunn et al. 2021)	t_0 (y)		-0.71	-1.33
		k (y^{-1})		0.260	0.160
		L_∞ (cm)		89.3	114.5
		CV		0.07	0.09
Length-weight	(Dunn et al. 2021)	a (g.cm^{-1})		2.34e-6	1.86e-6
		b		3.258	3.310
Stock recruitment relationship					
Stock recruitment steepness	(Horn & Francis 2010)	h	0.8		
Recruitment variability[2]		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		

1. Estimated in the base case assessment model.
2. Calculated in projections from the model Markov chain Monte Carlo runs.

Table 3: Maturity-at-age for Sub-Antarctic hake (Horn 2008).

Age	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Male	0.01	0.03	0.09	0.22	0.46	0.71	0.88	0.96	0.98	0.99	1.00	1.00	1.00	1.00
Female	0.01	0.02	0.05	0.11	0.23	0.43	0.64	0.81	0.91	0.96	0.98	0.99	1.00	1.00

2.1.3 Observations

Observational data for the Sub-Antarctic hake stock assessment included the biomass indices from the two series of Sub-Antarctic trawl surveys from the RV *Tangaroa* (Table 4, see also appendix A of Dunn et al. 2021). The first was the time series of surveys in November–December surveyed from 1992 to 2021 (November series, see Table 4); and the second was surveys in April–May from 1992 to 1998 (April–May series, see Table 4). An additional biomass index from September 1992 was not included in the base case assessment because it was the only survey in that time series. The November series of surveys was based on core strata from the Sub-Antarctic survey that had been sampled in each year, comprising 300–800 m depth strata and including 800–100 m depth strata in the Puysegur Bank region but excluding Bounty Plateau. The second series, April–May, comprised 300–800 m depth strata, excluding the 800–1000 m strata in the Puysegur Bank area and excluding the Bounty Plateau. The trawl survey series biomass indices and associated coefficients of variation (CVs) are given in Table 5.

CPUE indices from Dunn et al. (2021) were used in a sensitivity to the base case model. The CPUE index from the combined lognormal and binomial index from the daily summary CPUE index was used as an index of summer (time step two) vulnerable abundance (see table 17 of Dunn et al. 2021).

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. 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 trawl survey proportions-at-age are given in Table 6.

Age frequency observations for the trawl survey series were available for each of the surveys (Figure 3) and were included as unsexed proportions-at-age. The December 2016 Sub-Antarctic survey age frequency data were excluded because the core survey strata were unable to be completed in that year due to bad weather. The biomass estimates were scaled up using factors based on the proportion of hake biomass in those strata in previous surveys from 2000 to 2014, but there were too few otoliths sampled to generate a reliable age frequency. In addition, age data from the *Amaltal Explorer* survey in 1990 were included with an assumption that the age frequency observed in that survey was consistent with age frequencies from the later *Tangaroa* November survey series. Biomass estimates from the *Amaltal Explorer* surveys prior to the *Tangaroa* surveys were excluded as, though the selectivity of the surveys was likely to be similar, it was not known if the biomass estimates had the same overall catchability.

Commercial catch-at-age frequencies (Saunders et al. 2021) were available for most years (Table 4 and Figure 3) and were also included as unsexed proportions-at-age. These were assumed to be observations of the removals from the summary fishery. Estimates of the multinomial sample size (N) for the proportions-at-age observations were made via 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 6.

Ageing error was accounted for by modifying the likelihoods for the proportions-at-age data such that Ei 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).

Table 4: Observations used in the Sub-Antarctic hake stock assessment. Further summary details are given in appendix A of Dunn et al. (2021).

Data series	Model years
Survey biomass (*Tangaroa*, November)	1992–94, 2001–10, 2012–13, 2015, 2017, 2019, 2021
Survey proportions-at-age (*Tangaroa*, November)	1992–94, 2001–10, 2012–13, 2017, 2019, 2021
Survey proportions-at-age (*Amaltal Explorer*, November)	1990
Survey biomass (*Tangaroa*, September)	1992
Survey proportions-at-age (*Tangaroa*, September)	1992
Survey biomass (*Tangaroa*, April–May)	1992–93, 1996, 1998
Survey proportions-at-age (*Tangaroa*, April–May)	1992–93, 1996, 1998
CPUE (daily summary combined index)	1991–2020
Commercial trawl proportions-at-age	1990, 1992–94, 1996, 1998–2020

Table 5: Research survey indices (and associated CVs) for the Sub-Antarctic stock. Note the September series was not used in the base case mode for the stock assessment.

Model		November series [1]		April–May series [2]		September series [2]	
year	Vessel	Biomass (t)	CV	Biomass (t)	CV	Biomass (t)	CV
1992	*Tangaroa*	5 686	0.43	5 028	0.15	3 760	0.15
1993	*Tangaroa*	1 944	0.12	3 221	0.14		
1994	*Tangaroa*	2 567	0.12				
1996	*Tangaroa*			2 026	0.12		
1998	*Tangaroa*			2 554	0.18		
2001	*Tangaroa*	2 657	0.16				
2002	*Tangaroa*	2 170	0.20				
2003	*Tangaroa*	1 777	0.16				
2004	*Tangaroa*	1 672	0.23				
2005	*Tangaroa*	1 694	0.21				
2006	*Tangaroa*	1 459	0.17				
2007	*Tangaroa*	1 530	0.17				
2008	*Tangaroa*	2 470	0.15				
2009	*Tangaroa*	2 162	0.17				
2010	*Tangaroa*	1 442	0.20				
2012	*Tangaroa*	1 855	0.23				
2013[3]	*Tangaroa*	2 428	0.23				
2015	*Tangaroa*	1 477	0.25				
2017[3]	*Tangaroa*	1 373	0.34				
2019	*Tangaroa*	1 675	0.25				
2021	*Tangaroa*	1 572	0.20				

[1] Series based on indices from 300–800 m core strata, including the 800–1000 m strata in the Puysegur Bank area, but excluding Bounty Plateau.
[2] Series based on the biomass indices from 300–800 m core strata, excluding the 800–1000 m strata in the Puysegur Bank area and the Bounty Plateau.
[3] Due to bad weather, the core survey strata were unable to be completed in 2017; biomass estimates were scaled up using factors based on the proportion of hake biomass in those strata in previous surveys from 2000 to 2014.

Table 6: Catch-at-age data for the Sub-Antarctic stock, giving the multinomial initial and effective sample sizes assumed for each sample for the November and April-May trawl surveys, and the commercial catch-at-age data, 1990–2021.

Model	Trawl surveys				Commercial catch-at-age	
year	November		April–May		Initial	Effective
	Initial	Effective	Initial	Effective		
1990	50	12.99			111	13.29
1992	55	14.29	70	17.44	282	33.77
1993	78	20.27	68	16.94	222	26.58
1994	95	24.69			73	8.74
1996			51	12.70	80	9.58
1998			58	14.45	135	16.16
1999					255	30.53
2000					408	48.85
2001	153	39.76			237	28.38
2002	120	31.18			342	40.95
2003	138	35.86			157	18.80
2004	101	26.24			297	35.56
2005	80	20.79			98	11.73
2006	104	27.02			344	41.19
2007	135	35.08			98	11.73
2008	128	33.26			268	32.09
2009	155	40.28			291	34.84
2010	155	40.28			510	61.07
2011					398	47.66
2012	130	33.78			689	82.50
2013	157	40.80			435	52.09
2014					390	46.70
2015	59	15.33			297	35.56
2016					259	31.01
2017					255	30.53
2018					321	38.44
2019	54	14.03			147	17.60
2020					226	27.06
2021	71	18.45				

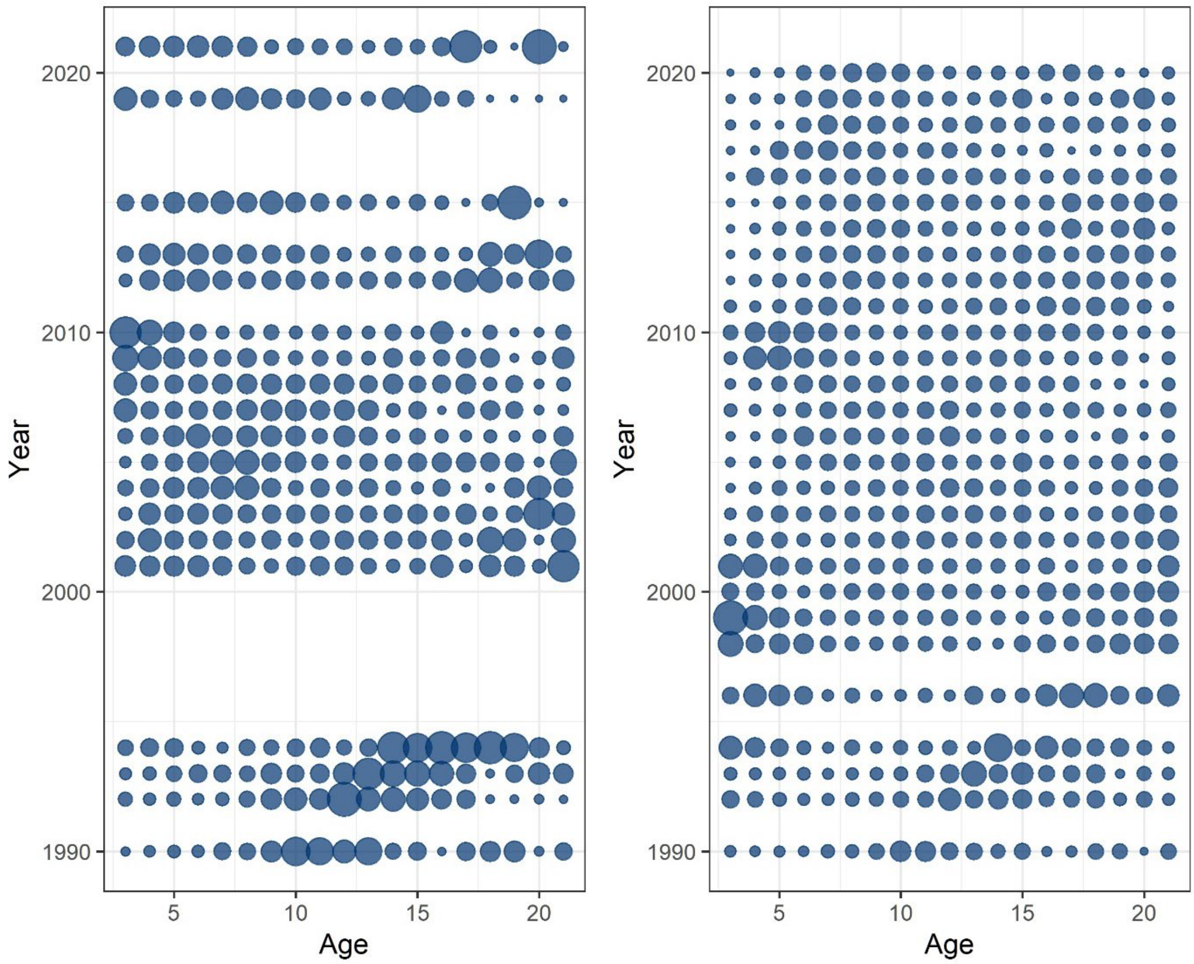


Figure 3: Relative proportions-at-age data from (left) the *Amaltal Explorer* (1990) and *Tangaroa* trawl survey series (1990—2021, November only), and (right) the commercial catch-at-age data, (1990–2020).

2.2 Model structure

Stock assessments have been carried out since include 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 Sub-Antarctic trawl survey, with a consistent time series since 1991 (Table 5). The most recent previous assessment was in 2019 (Dunn 2019). The model was structured with ages from 1 to 30 y, 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 1975 to 2021, and the annual cycle was broken into three discrete time steps, nominally an age correlation step (time step one), summer (September–March, time step two), and winter (April–August, time step three). The annual cycle assumed in the model is described in Table 7.

Initially, in the first time step, the age of all fish is 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 second (summer) time step, to be 50:50 male to female, and to be the mean (unfished) recruitment (R_0) multiplied by the spawning stock-recruitment relationship. Recruitment was assumed constant and equal to R_0 for years where adequate age frequency data were not available. Future recruitment was assumed to be lognormally distributed with variability observed in the estimated historical recruitment for each Markov chain Monte Carlo (MCMC) iteration.

The catch history for the fishery was split into summer and winter based on the relative reported catches in each season. For the years before 1991, when catch split information was not available, the ratio of catch between summer and winter was assumed to be a constant ratio of the annual landings, based on the mean proportion between summer and winter over the period 1991 and 2005. Fishing mortality 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. Selectivity for the summer and winter fishery was assumed to be the same because age data for the winter period were not available to allow the winter fishery selectivity to be estimated.

The fishing selectivity parameters were assumed to be logistic and 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 third (winter) time step. Maturation was specified as the time-invariant proportion of male and female fish-at-age that were mature and calculated as at the middle of the second (summer) time step.

The proportion of annual growth in each time step was based on the monthly estimates from the mean age-at-length growth model (Dunn et al. 2021) which indicates there was about 20% of the growth up to the mid-point of the summer time step, and then another 50% of growth up to the midpoint of the winter time step (see Table 7).

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 strengths to encourage estimates that averaged 1. Initial fits were evaluated at the mode 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 trawl fishery selectivity ogives were fitted as logistic curves; the research survey ogives were fitted as double normal curves. Selectivities were assumed to be constant for all years in each fishery or survey. The parameters estimated, their shape, prior assumptions, and bounds are summarised in Table 8.

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 priors on q for the *Tangaroa* trawl surveys were estimated assuming that the catchability constant was the product of areal availability (0.50–1.00), vertical availability (0.50–1.00), and vulnerability (0.01–0.50). The resulting (approximate lognormal) distribution had mean 0.16 and CV 0.79, with bounds assumed to be 0.01–0.40. 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.

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 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 7: Annual cycle of the Sub-Antarctic hake stock assessment model, giving the time steps, and the monthly timing of biological processes (ageing, recruitment, maturation, growth, natural mortality, and spawning) marked by X, and observations (resource surveys and associated age frequencies, and observer age frequencies (AFs), and CPUE indices (where used).

Monthly timing of biological and fisheries processes							Model timing of biological and fisheries processes				
	Recruitment	Maturation and spawning	Trawl catch (%)	*Tangaroa* resource surveys (Biomass and AFs)	Fishery AFs	Fishery CPUE	Model timestep	Ageing	Proportion of growth	Proportion of natural mortality	Trawl catch (%)
							Year start	X			
Sep	X		17	1 (Sept 1992)			1		0.00	0.58	78
Oct			22								
Nov		X	18								
Dec			9	19 (Dec 1990 to 2020)	X	X					
Jan			6				2		0.33	0.42	21
Feb			3								
Mar			3								
Apr			3	4 (Apr 1992 to 1998)							
May			4								
Jun			1								
Jul			2								
Aug			11								
							Year end		0.67		

Table 8: The assumed priors for key distributions (when estimated) for the Sub-Antarctic 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[1]	Lognormal (μ, CV)	0.16	0.79	0.01	0.40
CPUE q	Uniform-log	–	–	1e-8	1e-3
Selectivities	Uniform	–	–	1	25–200[2]
M	Normal (μ, SD)	0.19	0.05	0.05	0.40

[1] Three trawl survey q values were estimated, but all had the same priors.
[2] 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 was developed. This included revised trawl survey biomass estimates for earlier years (where the biomass estimate for the incorrect area had been assumed in the previous assessments), and new biomass and age frequency trawl survey observations since the last assessment, i.e., the two surveys in November 2018 and 2020, as well as new commercial catch data for the 2019 and 2020 fishing years. The revised CPUE indices for 1991–2020 were included as a sensitivity model only. The base case model also updated the annual cycle, with a revised catch history (see Dunn et al. 2021).

An audit trail implementing the changes between the 2019 base case assessment model (with σ_R assumed to be 1.1), and this was sequentially updated to investigate the effect of changes in model assumptions, revised data, and the impact of the new observations on the model outcomes (Table 9). The revised catch history and the correction of the biomass indices from previous surveys increased the initial biomass and current stock status slightly. Updating of the year class strength priors, revised annual cycle, and revised observation timing had little impact on initial or current status. The inclusion of the recent biomass indices, survey age data, and commercial catch-at-age data increased the initial biomass and current status slightly. The use of the revised biological parameters had a negligible effect on the model outcomes. After applying data weighting (process error) to the biomass indices and age frequency data, the base case model increased the estimate of initial biomass (B_0) from about 55 000 t to 60 300 t, and current status increased from 45% B_0 in 2018 to 63% in 2018 for the current model (Table 9). Much of the difference in current status for Sub-Antarctic hake between the previous model of Dunn (2019) and the current base case model occurred in the most recent ten years, where the effect of the updated biomass indices from the trawl survey did not indicate the same level of decline as was assumed previously. The estimated MPD stock trajectories for the base case model are given in Figure 4.

Model fits to the survey data (Figure 5 and Figure 6) were adequate and did not suggest any strong evidence of departure from model assumptions, as were the fits to the age data for the November survey series (Figure 7 and Figure 8), April–May survey series (Figure 9), and the commercial catch-at-age data (Figure 10 and Figure 11).

Selectivity parameters (Figure 12) were reasonable, with some evidence of a slight decline in the right-hand limb of the November trawl survey series, but a much steeper decline in the right-hand limb for the April–May survey series. 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 13. This indicated a period of very strong year classes in the late 1970s, with a strong year class in 1980. Since then, year classes have been about average with little variation. Data from the trawl surveys (Figure 6) and the commercial proportions-at-age data (see Figure 3) were consistent with the estimated year classes, with the observations of strong year classes from those years persisting in both the observed trawl survey and commercial catch-at-age proportions until the mid-2000s. The pattern of a few large year classes at the advent of the fishery but low variation since may be considered unusual. However, the change in the biomass from the April–May survey series and the strong year classes in the proportions-at-age data support the model estimates. Sensitivity analyses (see later) suggested that models that excluded these early data were similar to those models that included these data.

Little information was available in the model to estimate the stock recruitment relationship, most likely because the population trajectory had not declined to a point where the stock recruitment relationship had an impact on model outcomes. The stock recruitment relationship and estimated recruitments are shown in Figure 14.

MPD profiles on B_0 (Figure 15), however, suggested that the information contained in the model observations about the absolute level of biomass was weak. Although the proportions-at-age data from the fishery and the surveys indicated that lower estimates of B_0 were unlikely, few data had any information about how high biomass may be—the only constraint on the upper end of biomass estimates was driven by priors on the trawl survey catchability coefficient.

Table 9: Audit trail from the 2018 base case to the 2021 base case model run (MPD). The data were not re-weighted between models. Biomass is given in tonnes.

Model	B_0	B_{2018}	B_{2018} (% B_0)	B_{2021}	B_{2021} (% B_0)
(a) 2018 Base (sigmaR1.1) (Dunn 2019)	55 010	24 600	44.7	–	–
(b) Undo process error	66 760	32 010	47.9	–	–
(c) Revise catch history	67 130	32 360	48.2	–	–
(d) Correct the survey series error	70 220	36 760	52.3	–	–
(e) Update to final year = 2021	71 480	37 230	52.1	31 810	44.5
(f) Update year class strength priors	69 570	36 280	52.1	31 180	44.8
(g) Update year class strength mean	65 940	36 250	55.0	31 150	47.2
(h) Revise Annual Cycle	65 850	35 900	54.5	30 790	46.8
(i) Revise observation timing	68 430	35 300	51.6	30 310	44.3
(j) Add survey biomass data	71 490	37 900	53.0	38 320	53.6
(k) Add survey age data	73 920	41 220	55.8	36 550	49.4
(l) Add catch-at-age observations	73 920	41 220	55.8	36 550	49.4
(m) Split catch	72 890	44 090	60.5	40 690	55.8
(n) Update biological parameters	70 930	42 180	59.5	38 600	54.4
(o) Revise process error	60 270	37 980	63.0	35 730	59.3
(R1.0) 2021 base case	60 270	37 980	63.0	35 730	59.3

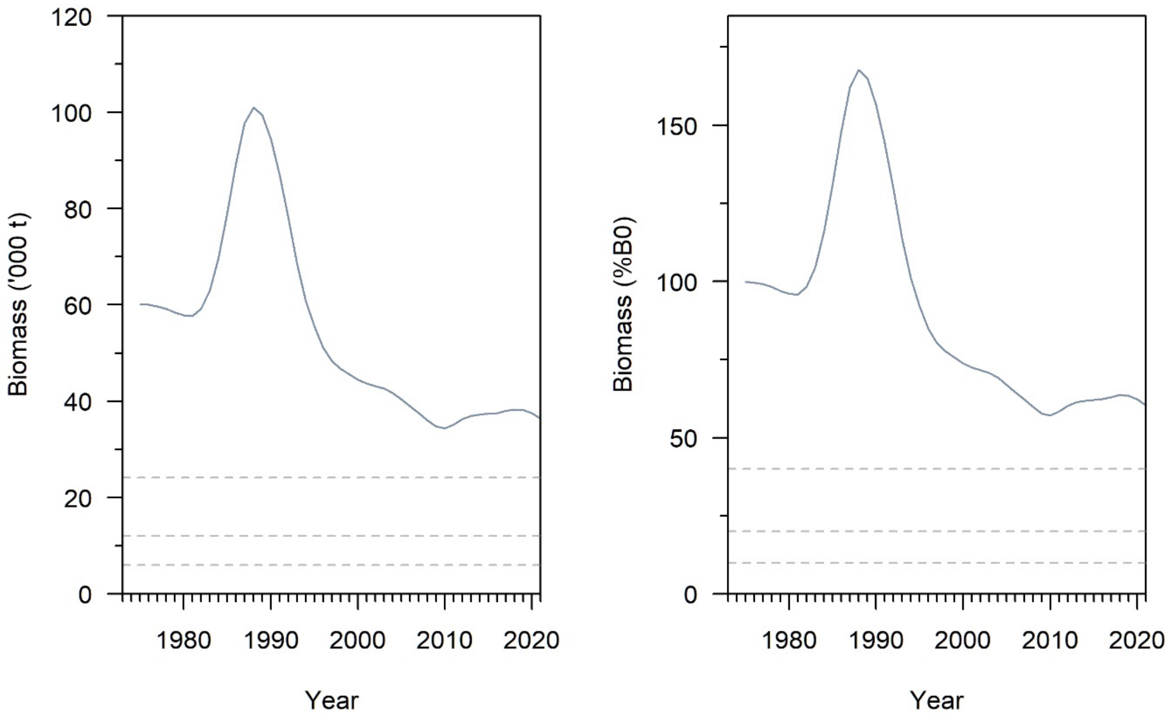


Figure 4: Base case model MPD trajectories for (left) *SSB* biomass and (right) stock status (*SSB*) as a percent of B_0.

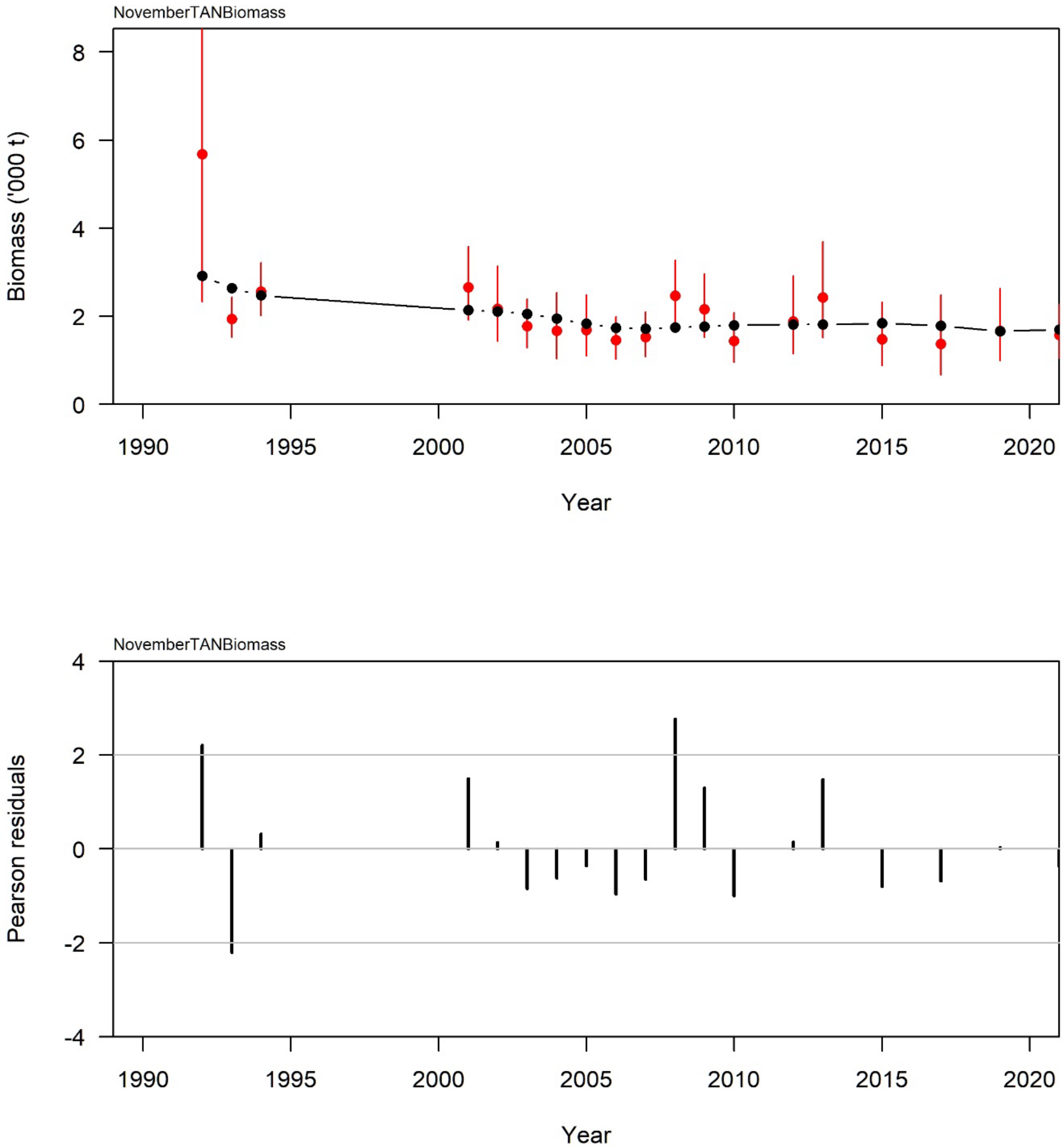
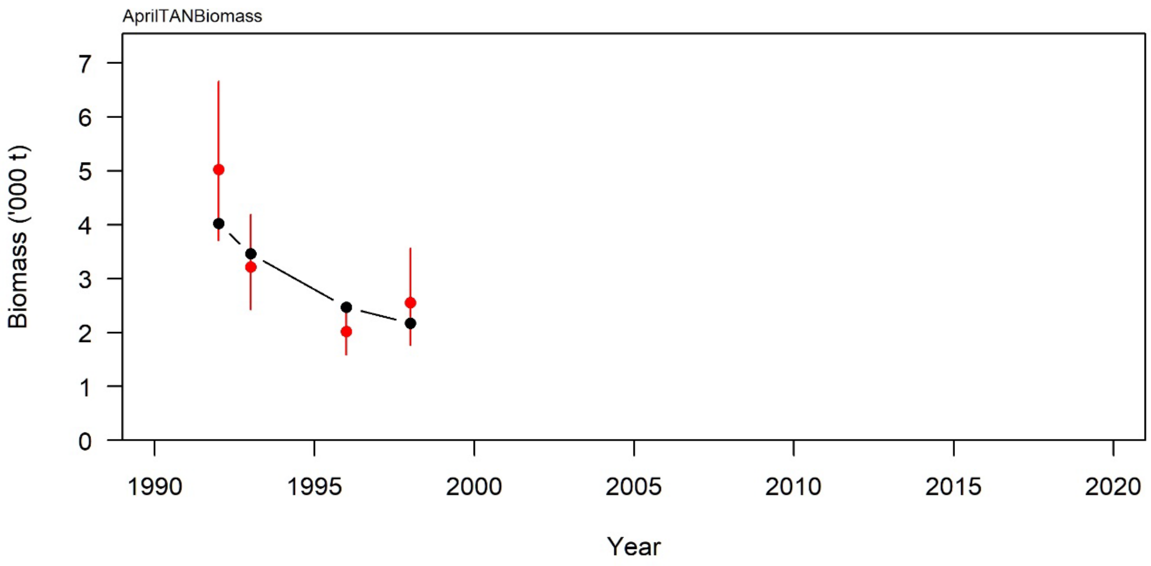


Figure 5: Base case MPD model fits to the November survey time series for (top) observed biomass (red circles and 95% credible intervals indicated by the red lines) and expected values by black points; and (bottom) Pearson residuals by year for the model fits.



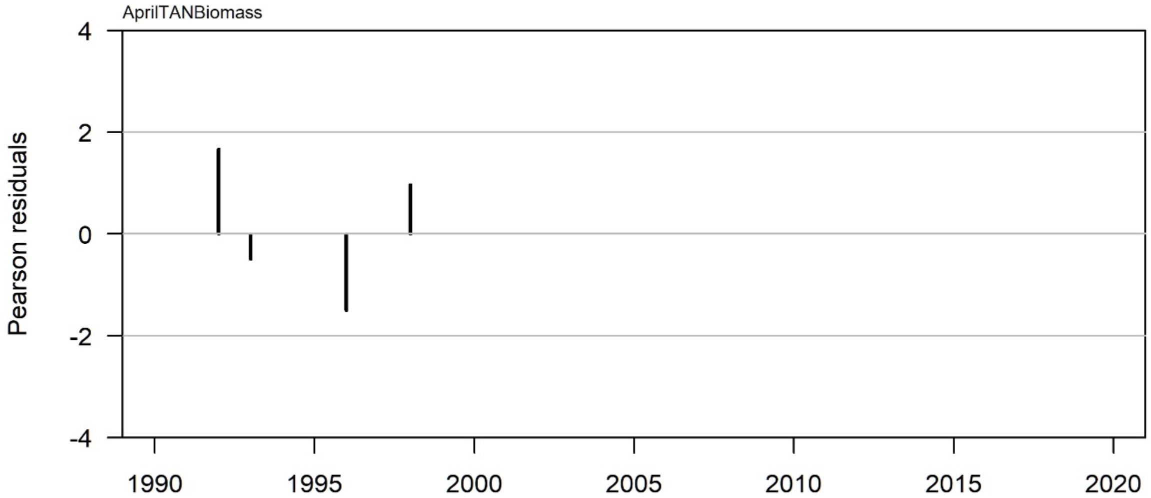


Figure 6: Base case MPD model fits to the April–May survey time series for (top) observed biomass (red circles and 95% intervals indicated by the red lines) and expected values by black points; and (bottom) Pearson residuals by year for the model fits.

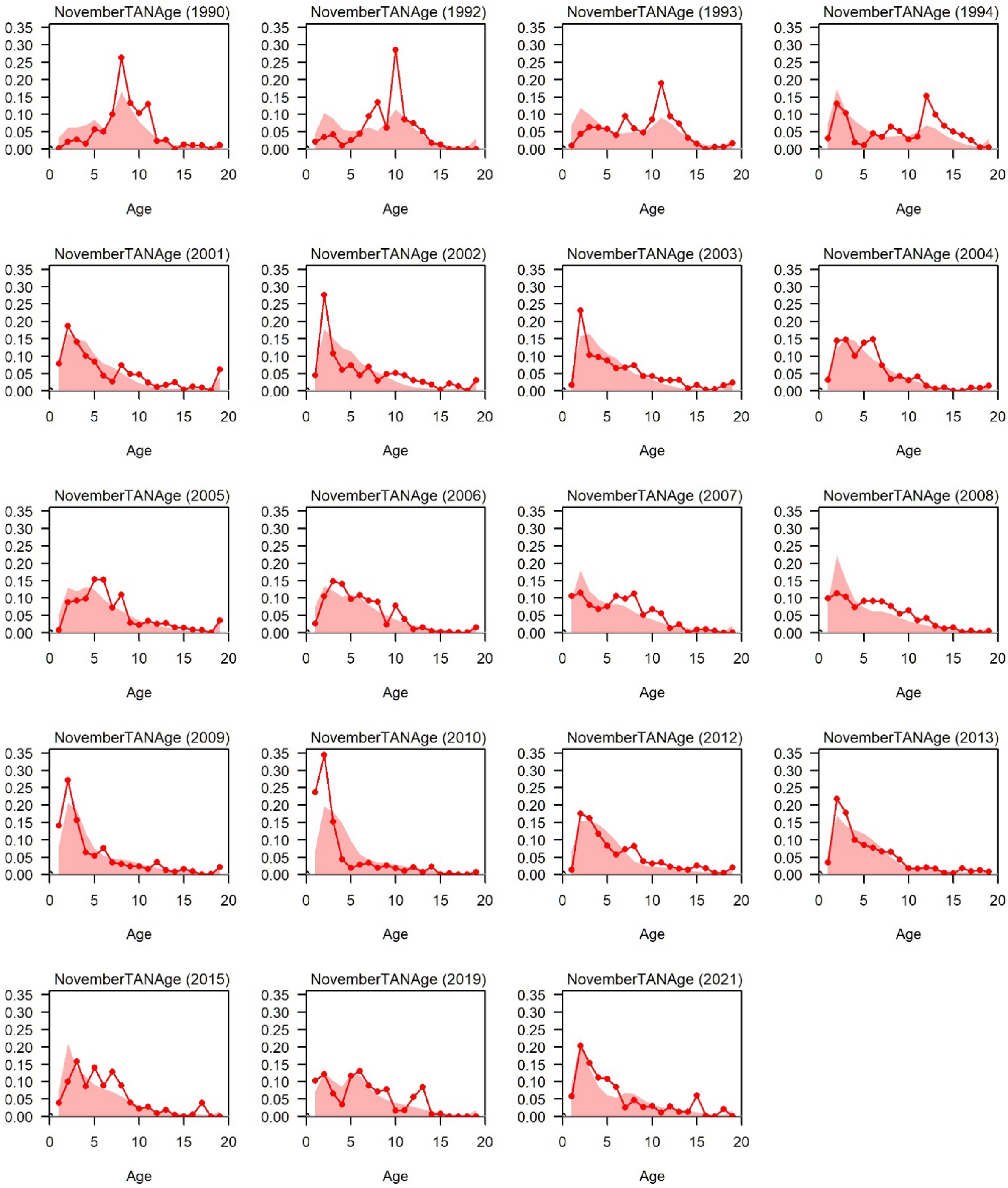


Figure 7: Base case model observed (red points and lines) and expected (shaded red polygons) of the proportions-at-age data from the November survey time series for 1990–2021.

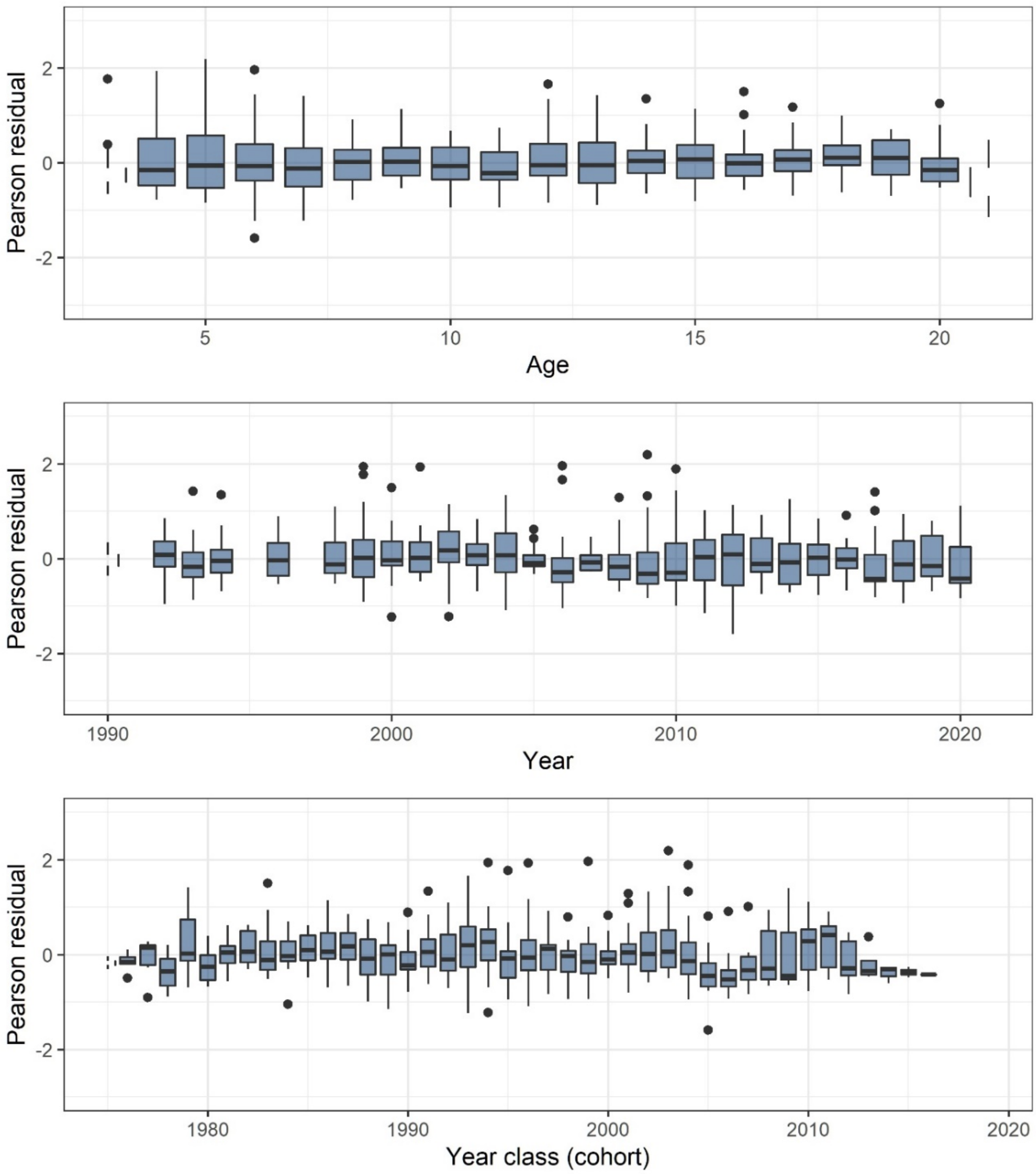


Figure 8: Pearson residuals for the base case MPD model fits to the proportions-at-age data from the November survey time series for (top) observed age, (middle) year of observations, and (bottom) cohort observed (solid black lines indicate the median, blue boxes the interquartile range, vertical lines are 1.5 times the interquartile range, and black circles are observations outside 1.5 times interquartile range).

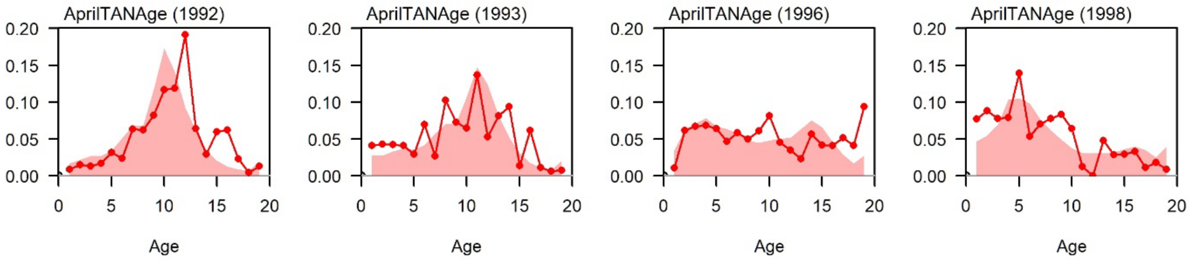


Figure 9: Base case model observed (red points and lines) and expected (shaded red polygons) of the proportions-at-age data from the April–May survey time series for 1992–1998.

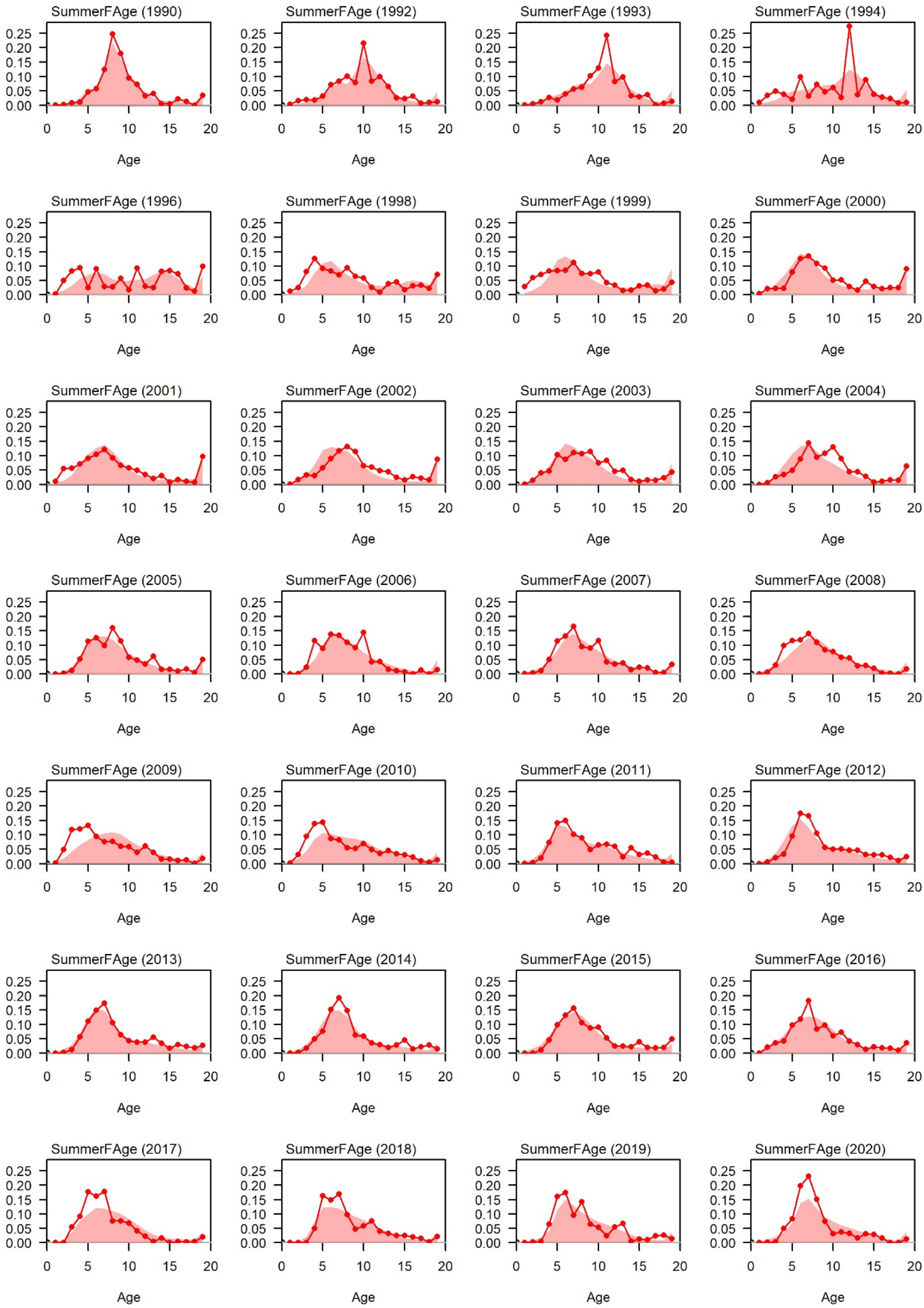


Figure 10: Base case model observed (red points and lines) and expected (shaded red polygons) of the proportions-at-age data from the commercial catch-at-age time series for 1990–2020.

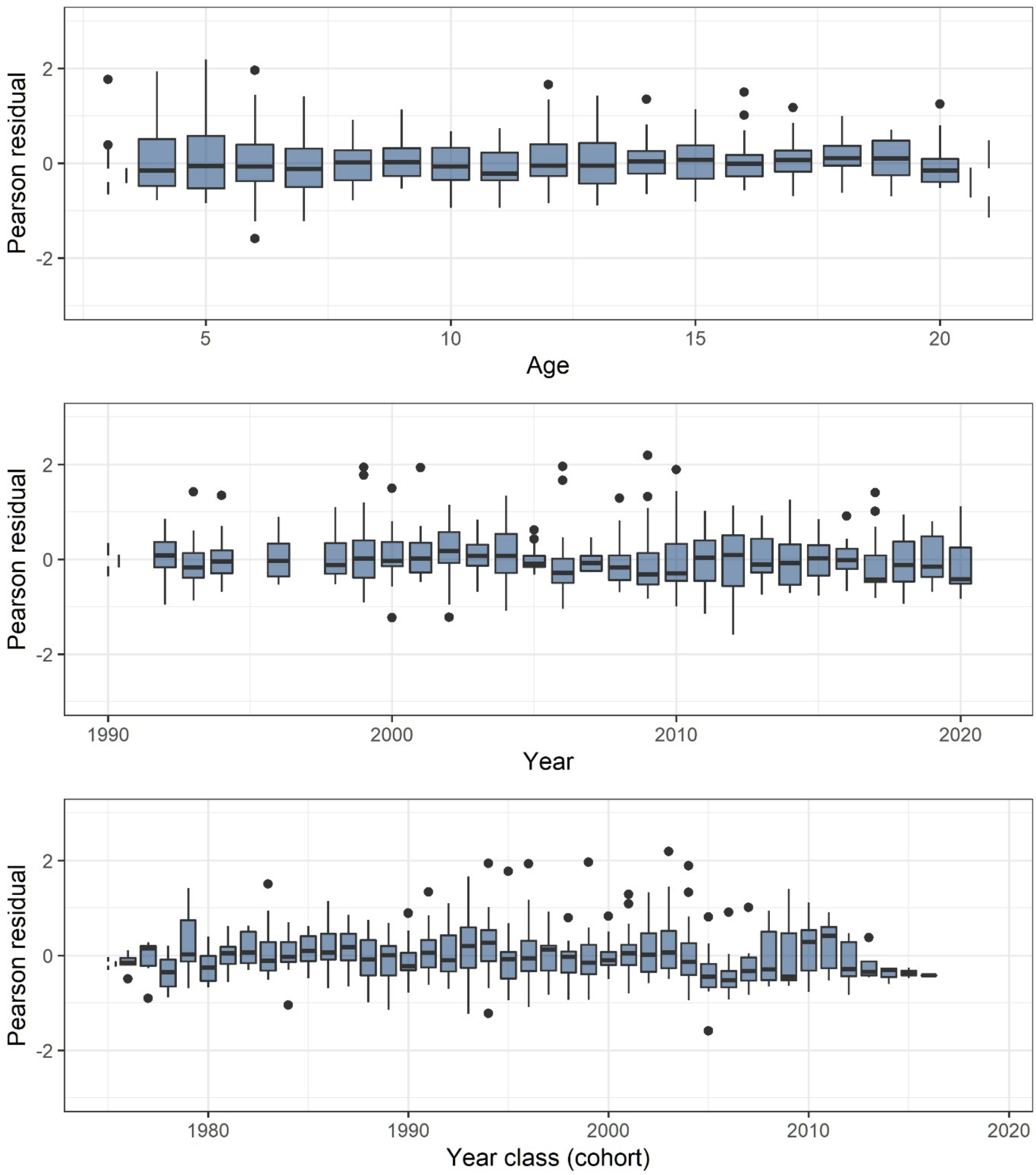


Figure 11: Pearson residuals for the base case MPD model fits to the proportions-at-age data from the commercial fishery for (top) observed age, (middle) year of observations, and (bottom) cohort observed (solid black lines indicate the median, blue boxes the interquartile range, vertical lines are 1.5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

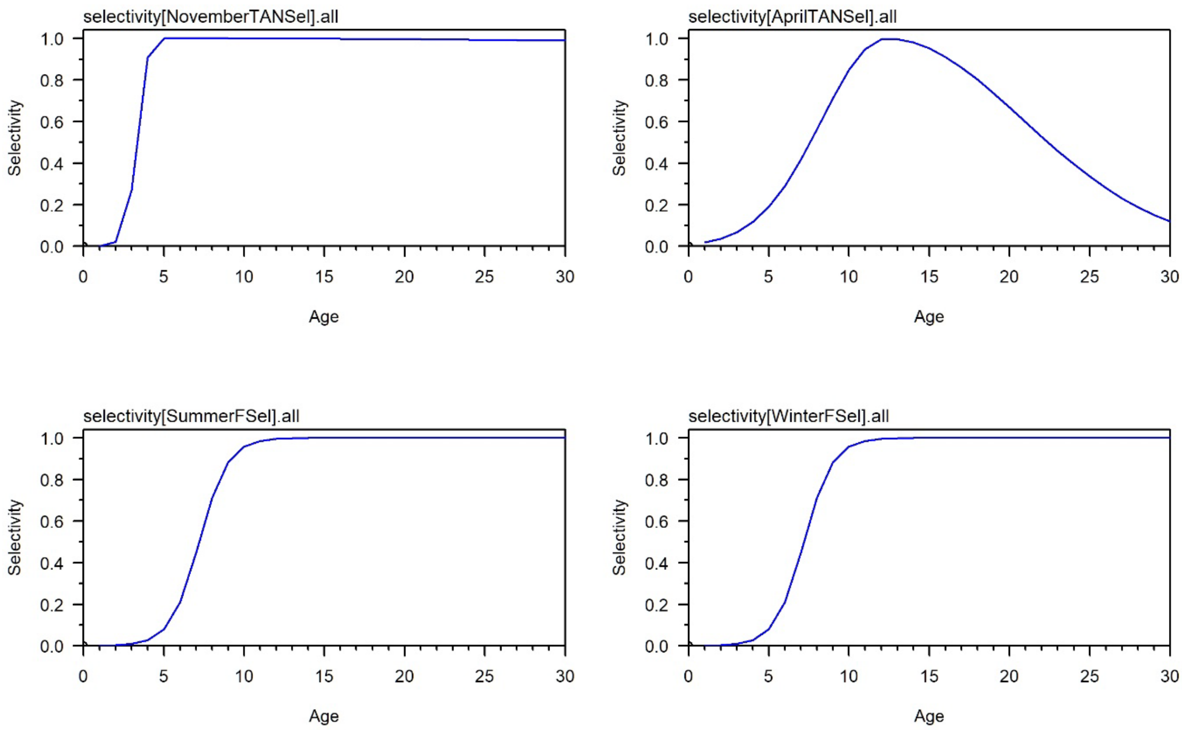


Figure 12: Base case model estimates of the selectivity parameters for the November survey time series (top left), the April–May survey time series (top right), the commercial catch for the summer fishery (bottom left), and the assumed winter selectivity (set equal to the summer selectivity) (bottom right).

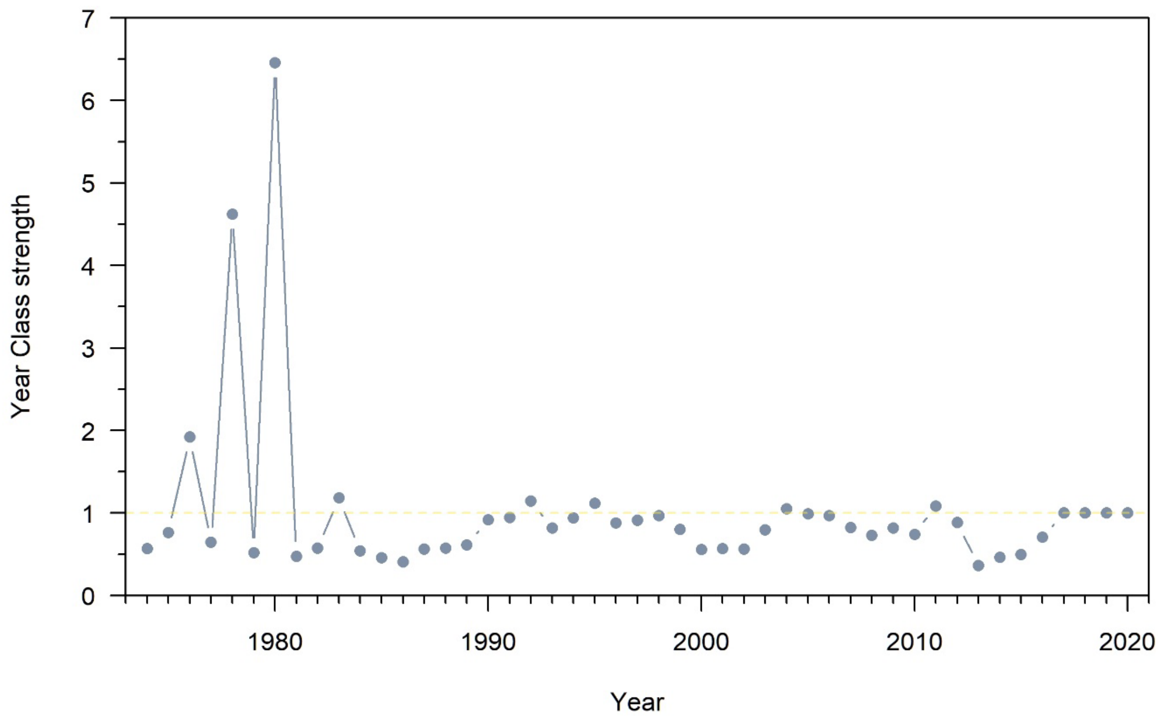


Figure 13: Base case model estimates of the relative year class strength parameters; estimated for 1974–2016 and assumed equal to 1 for 2017–2020.

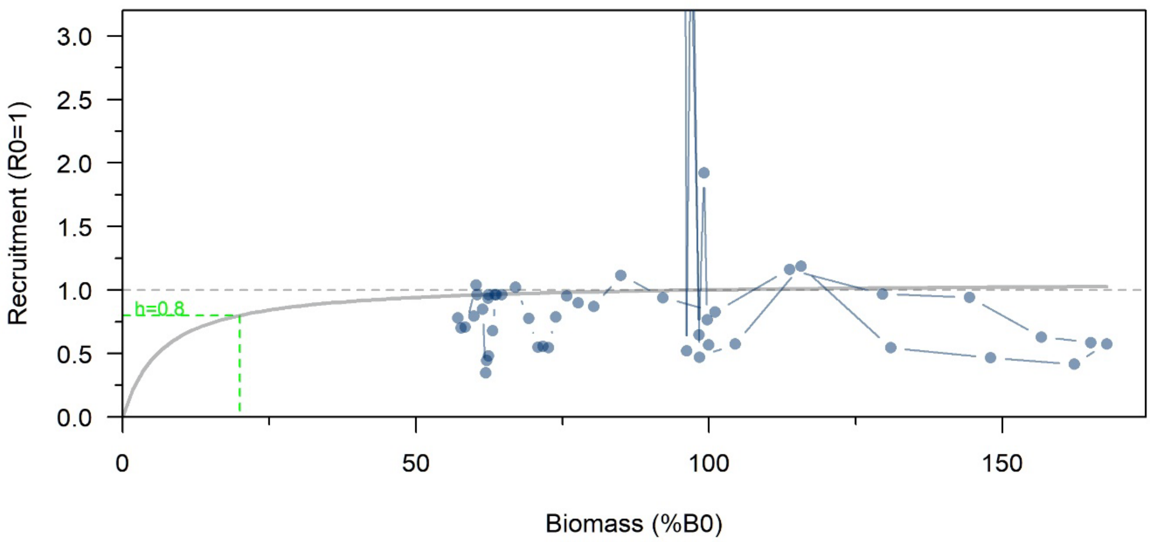


Figure 14: The stock recruitment relationship (Beverton-Holt with steepness *h* = 0.8), and the relative recruitment values (y-axis) plotted against *SSB* (x-axis) for the base case model.

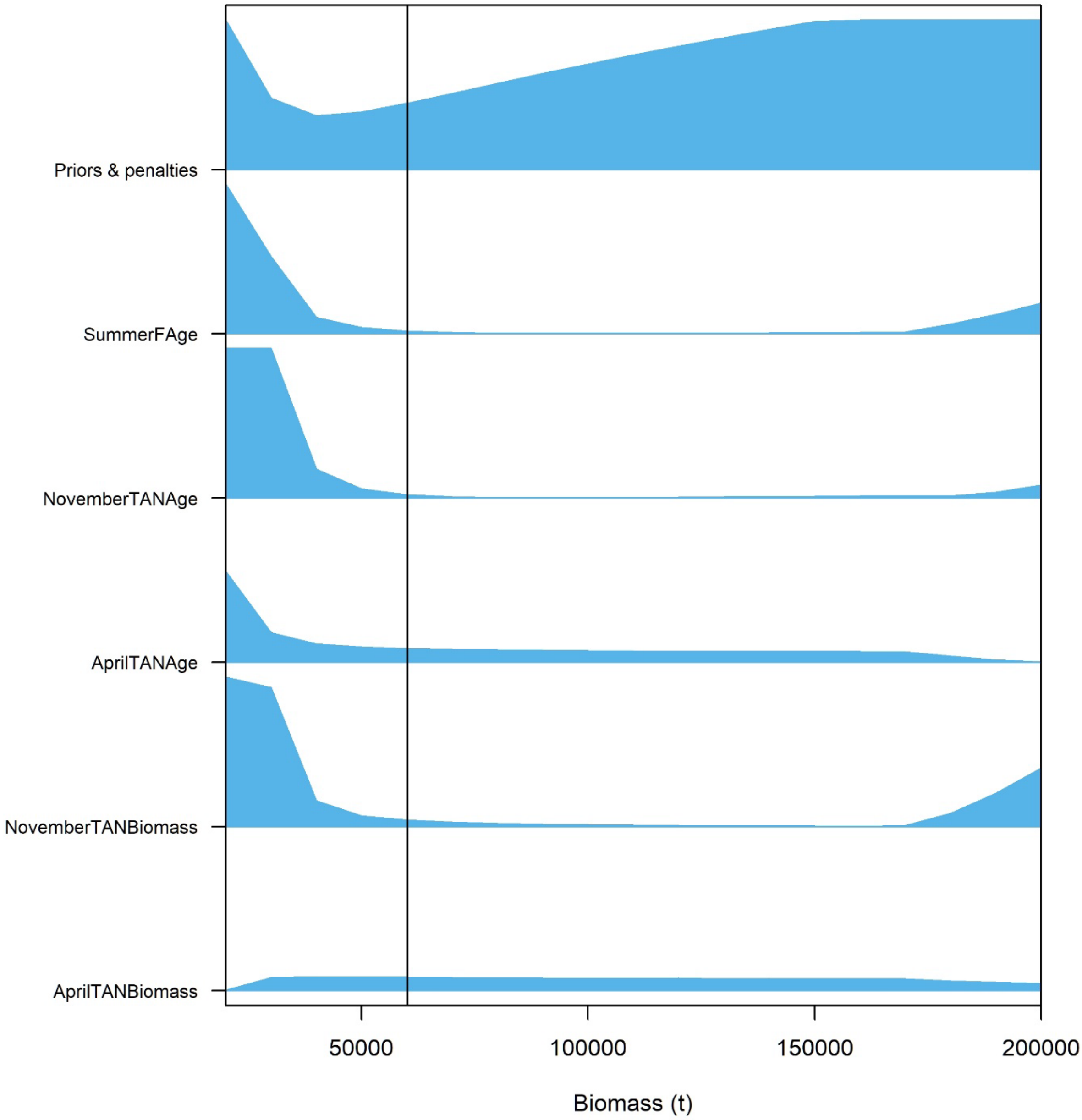


Figure 15: MPD profiles for B_0 using the base case model for the penalties and priors, and each time series of observations. Values were truncated to the maximum height in each graph (10 negative log likelihood (NLL) points).

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 10). Sensitivities used the base case model 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 fitted to CPUE or assumed a low value for natural mortality.

Sensitivities showed that including the September *Tangaroa* survey (model a) had no significant effect on either the model fits or outcomes. Similarly, removing the age frequency data from the *Amaltal Explorer* survey in 1990, nor removing the early commercial catch age data up to 1999 (model b) had little effect. Fixing the early year class strengths at one for 1974–1980 (model c) and removing the early November survey proportions-at-age data for 1990–1994 (model d) also had little effect on model fits or outcomes. Here, the models estimate of the increase in abundance in the late 1980s and early 1990s was reduced and fits to later data introduced some evidence of slightly poorer fit.

The use of daily summary CPUE (and downweighting of the November trawl survey series) resulted in a slightly lower initial biomass and current status, as did assuming much lower productivity with $M = 0.15$ y^{-1}. Overall, none of the sensitivities altered the outcome of the base case model in any significant manner, with the sensitivities indicating a stock status of between 49 and 66% B_0 (Table 10).

Other sensitivities (not shown) that reduced the variability assumed in the year class strength estimates ($\sigma_R = 0.7$ instead of 1.1) modified the ratio of catch to either winter or summer for years before the catch split information was available or, using a logistic selectivity for the November survey time series, had only small effects on the model estimates of initial biomass or current stock status.

Table 10: Sensitivity models (MPD) to the 2021 base case stock assessment model for Sub-Antarctic hake. OBS is observer data, YCS is year class strength, TAN is *Tangaroa* survey, AEX is *Amatal Explorer* survey.

Model	B_0	B_{2018}	B_{2018} (% B_0)	B_{2021}	B_{2021} (% B_0)	Est. M
2021 base	60 180	38 330	63.7	36 370	60.4	0.225
(a) Include September	58 910	37 010	62.8	35 240	59.8	0.218
(b) Remove early age data (OBS)	56 860	35 870	63.1	34 590	60.8	0.218
(c) Remove early age data (OBS+fixed YCS)	51 190	31 990	62.5	31 680	61.9	0.196
(d) Remove early age data (OBS+fixed YCS+TAN)	45 040	26 920	59.8	26 910	59.7	0.194
(e) CPUE cv=0.2 (down weight surveys)	55 460	29 160	52.6	27 360	49.3	0.224
(f) Loose M Prior	61 330	39 180	63.9	37 140	60.6	0.226
(g) Fixed YCS	42 440	24 740	58.3	27 090	63.8	0.193
(h) Fixed M=0.15 y^{-1}	40 730	20 840	51.2	20 760	51.0	–
(i) Fixed M=0.19 y^{-1}	53 560	33 270	62.1	31 880	59.5	–
(j) Fixed M=0.23 y^{-1}	80 310	56 730	70.6	53 170	66.2	–
(k) 2021 base (excluding AEX 1990 age frequencies)	60 380	38 420	63.6	36 150	59.9	0.223

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_{2021}), and current status (B_{2021} as a percent of B_0) are given in Table 11. Estimates of catchability parameters and natural mortality are given in Table 12.

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 16). Model estimates of initial biomass and current biomass (Figure 17) were relatively symmetric, and comparisons of MCMC chains did not indicate any evidence of non-convergence. Estimates of the trawl survey catchability (Figure 18) 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 November and April–May survey biomass indices (Figure 19 and Figure 20, respectively) were reasonable and indicated a good fit of the MCMCs to the abundance biomass data. Model estimates of the selectivity parameters (Figure 21) indicated good evidence that the November selectivity was only slightly domed, and may plausibly be logistic, whereas the April–May survey had considerably more evidence for a domed selectivity.

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 as 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 22).

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 showed a high level of consistency between chains (Figure 17) and diagnostics did not indicate any evidence of non-convergence for the key output parameters. 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 11: Estimates (t) of B_0 and current status for the base case and sensitivity models for the Sub-Antarctic hake assessment model. OBS is observer data, YCS is year class strength, AF is age frequency, TAN is *Tangaroa* survey, AEX is *Amatal Explorer* survey.

Model	B_0	B_{2021}	B_{2021} (% B_0)
2021 base	59 000 (43 220–93 600)	36 490 (22 250–65 510)	61.7 (49.5–75.1)
(a) Include September	55 460 (41 900–84 910)	33 440 (21 110–58 540)	59.8 (48.2–73.6)
(b) Remove age data (OBS)	56 120 (41 490–91 960)	34 830 (21 200–65 440)	61.9 (48.9–75.8)
(c) Remove AF data (+fixed YCS)	46 600 (38 360–68 400)	30 160 (19 130–53 120)	64.2 (49.5–81.1)
(d) Remove AF data (+TAN)	41 470 (36 080–56 980)	24 680 (15 730–44 470)	59.2 (43.1–77.7)
(e) CPUE CV = 0.2 (down weight surveys)	53 400 (42 140–77 240)	26 570 (18 420–43 580)	49.8 (41.8–59.5)
(f) Loose *M* Prior	59 530 (43 190–100 120)	36 920 (22 420–67 750)	61.8 (49.6–75.3)
(g) Fixed YCS	41 420 (37 480–50 280)	28 250 (22 220–39 560)	68.2 (58.1–78.7)
(h) Fixed M=0.15 y^{-1}	40 440 (36 050–46 170)	20 990 (14 970–28 760)	51.9 (40.9–64.0)
(i) Fixed M=0.19 y^{-1}	54 000 (44 370–68 640)	32 930 (22 920–49 070)	61.3 (49.8–75.0)
(j) Fixed M=0.23 y^{-1}	75 130 (55 310–110 190)	51 700 (33 480–85 480)	68.6 (54.8–84.2)
(k) 2021 base (excluding AEX 1990 AFs)	58 570 (43 150–91 100)	36 140 (22 250–62 480)	61.5 (49.5–75.2)

Table 12: Estimates of key parameters (survey catchability estimates and natural mortality values) for the base case and sensitivity models for the Sub-Antarctic hake assessment model. OBS is observer data, AF is age frequency, YCS is year class strength, TAN is *Tangaroa* survey, AEX is *Amatal Explorer* survey.

Model	November survey *q*	April–May *q*	M y^{-1}
2021 base	0.033 (0.018–0.051)	0.059 (0.033–0.098)	0.198 (0.173–0.225)
(a) Include September	0.035 (0.022–0.053)	0.063 (0.038–0.101)	0.194 (0.169–0.218)
(b) Remove age data (OBS)	0.036 (0.020–0.057)	0.063 (0.034–0.102)	0.189 (0.159–0.218)
(c) Remove AF data (+fixed YCS)	0.047 (0.027–0.068)	0.089 (0.053–0.145)	0.167 (0.140–0.196)
(d) Remove AF data (+TAN)	0.056 (0.031–0.080)	0.147 (0.075–0.252)	0.153 (0.122–0.194)
(e) CPUE CV = 0.2 (down weight surveys)	0.037 (0.024–0.051)	0.063 (0.039–0.098)	0.198 (0.175–0.224)
(f) Loose *M* Prior	0.032 (0.017–0.050)	0.059 (0.031–0.098)	0.199 (0.172–0.226)
(g) Fixed YCS	0.073 (0.050–0.104)	0.150 (0.102–0.233)	0.165 (0.142–0.193)
(h) Fixed M=0.15 y^{-1}	0.060 (0.050–0.072)	0.102 (0.076–0.146)	–
(i) Fixed M=0.19 y^{-1}	0.037 (0.027–0.047)	0.066 (0.047–0.098)	–
(j) Fixed M=0.23 y^{-1}	0.032 (0.018–0.054)	0.051 (0.031–0.092)	–
(k) 2021 base (excluding AEX 1990 AFs)	0.033 (0.019–0.051)	0.060 (0.035–0.100)	0.199 (0.172–0.223)

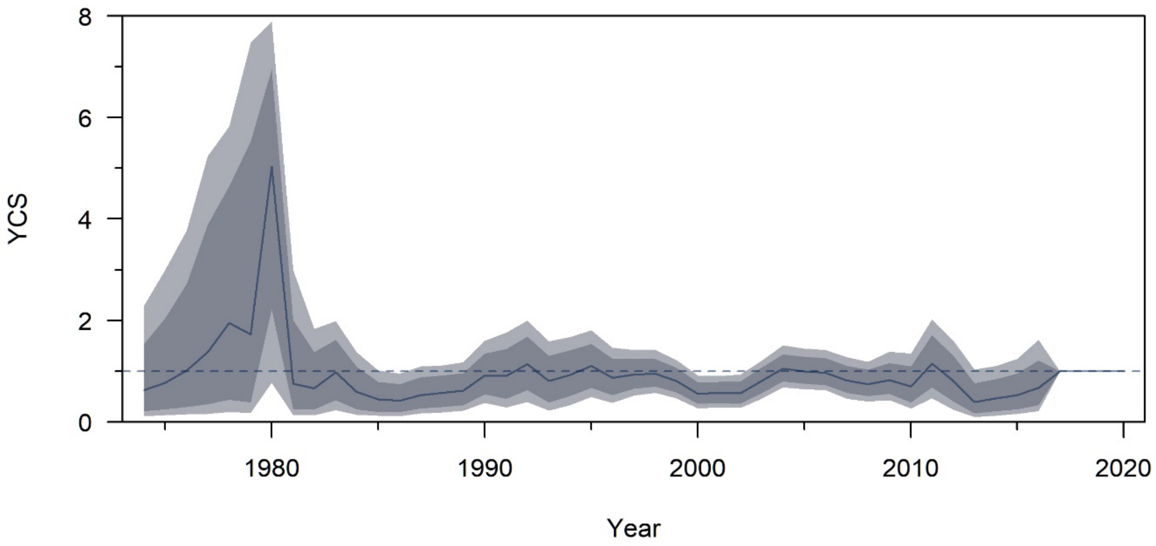


Figure 16: Base case model posterior distribution of year class strengths for years 1974–2016. The blue line indicates the median trajectory, the dark shaded area indicates the 80% credible interval, and the light shaded area indicates the 95% credible interval. The dotted horizontal line indicates the average of one.

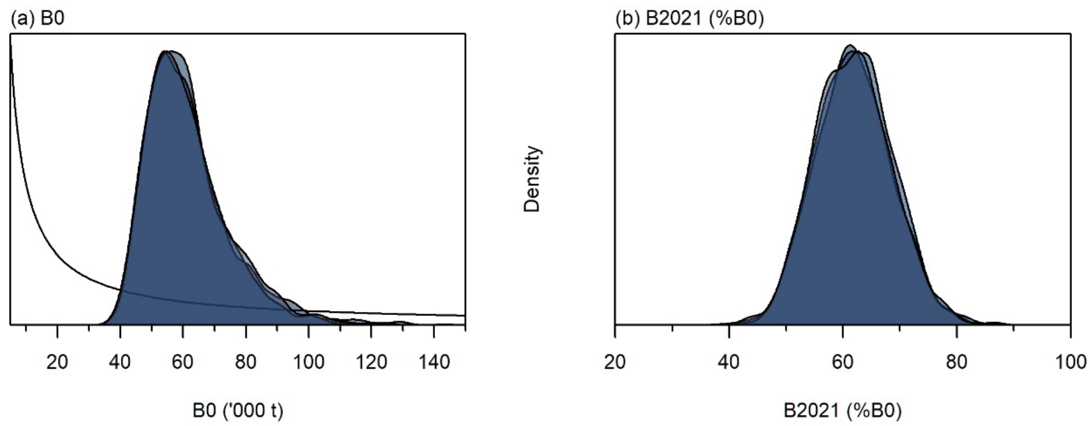


Figure 17: Base case model posterior distributions of (left) B_0 and (right) B_{2021} as a percent of B_0 for the three MCMC chains. The prior for B_0 is shown on the left figure as a line.

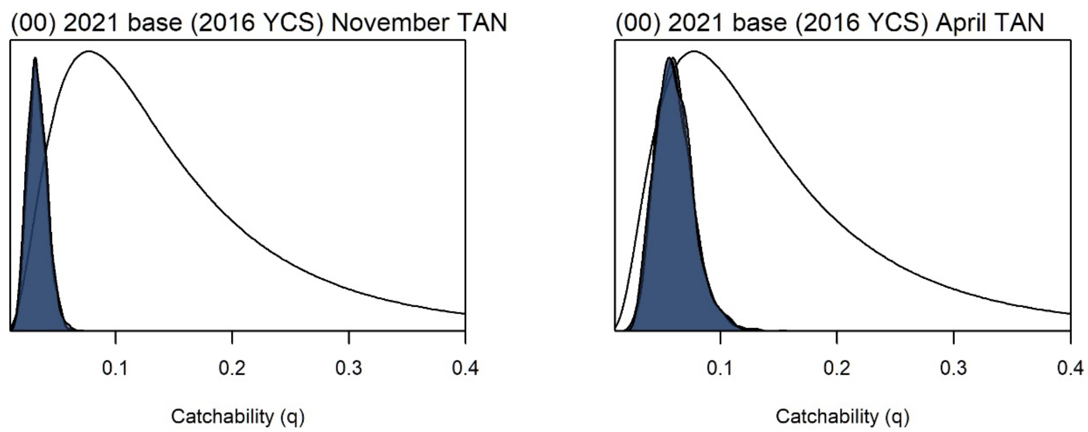


Figure 18: Base case model posterior distributions of (left) November series catchability (right) April–May series catchability for the three MCMC chains. The prior for the catchability is shown on the left figure as a line.

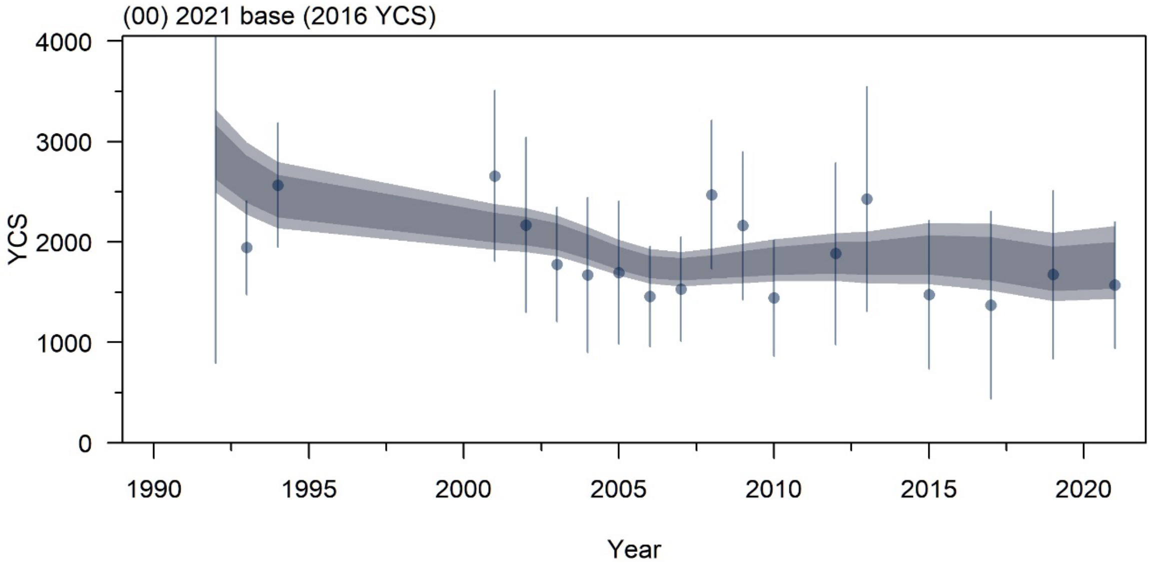


Figure 19: Base case model posterior distribution of the expected values for the November survey series. Observed values (and 95% confidence intervals) are shown as vertical lines. The prior for B_0 is shown on the left figure as a line. The dark shaded area indicates the 80% credible interval, and the light shaded area indicates the 95% credible interval.

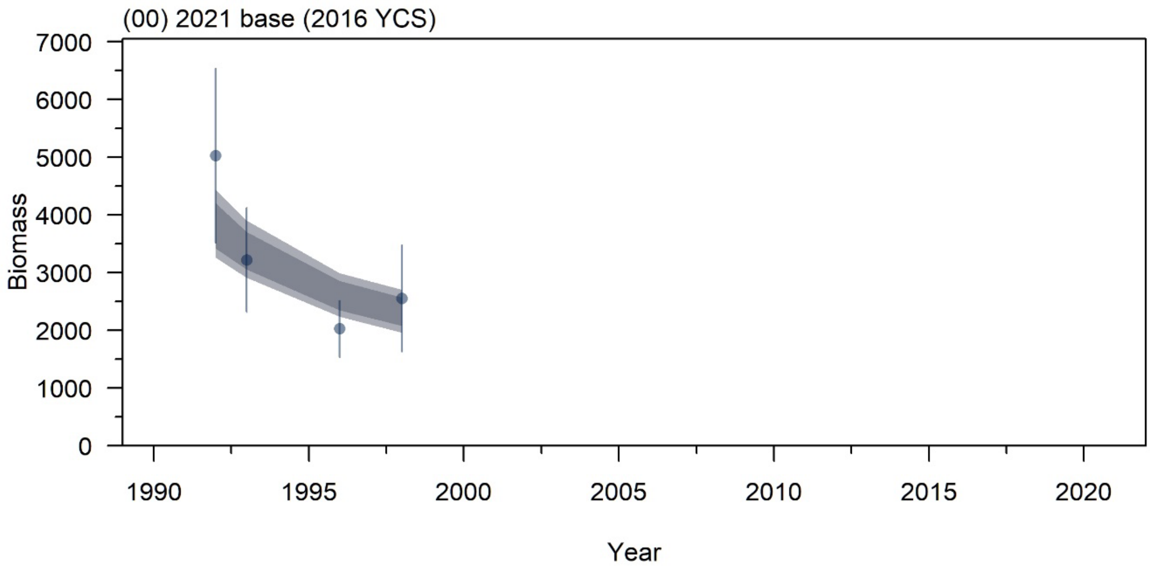


Figure 20: Base case model posterior distribution of the expected values for the April–May survey series. Observed values (and 95% confidence intervals) are shows as vertical lines. The prior for B_0 is shown on the left figure as a line. The dark shaded area indicates the 80% credible interval, and the light shaded area indicates the 95% credible interval.

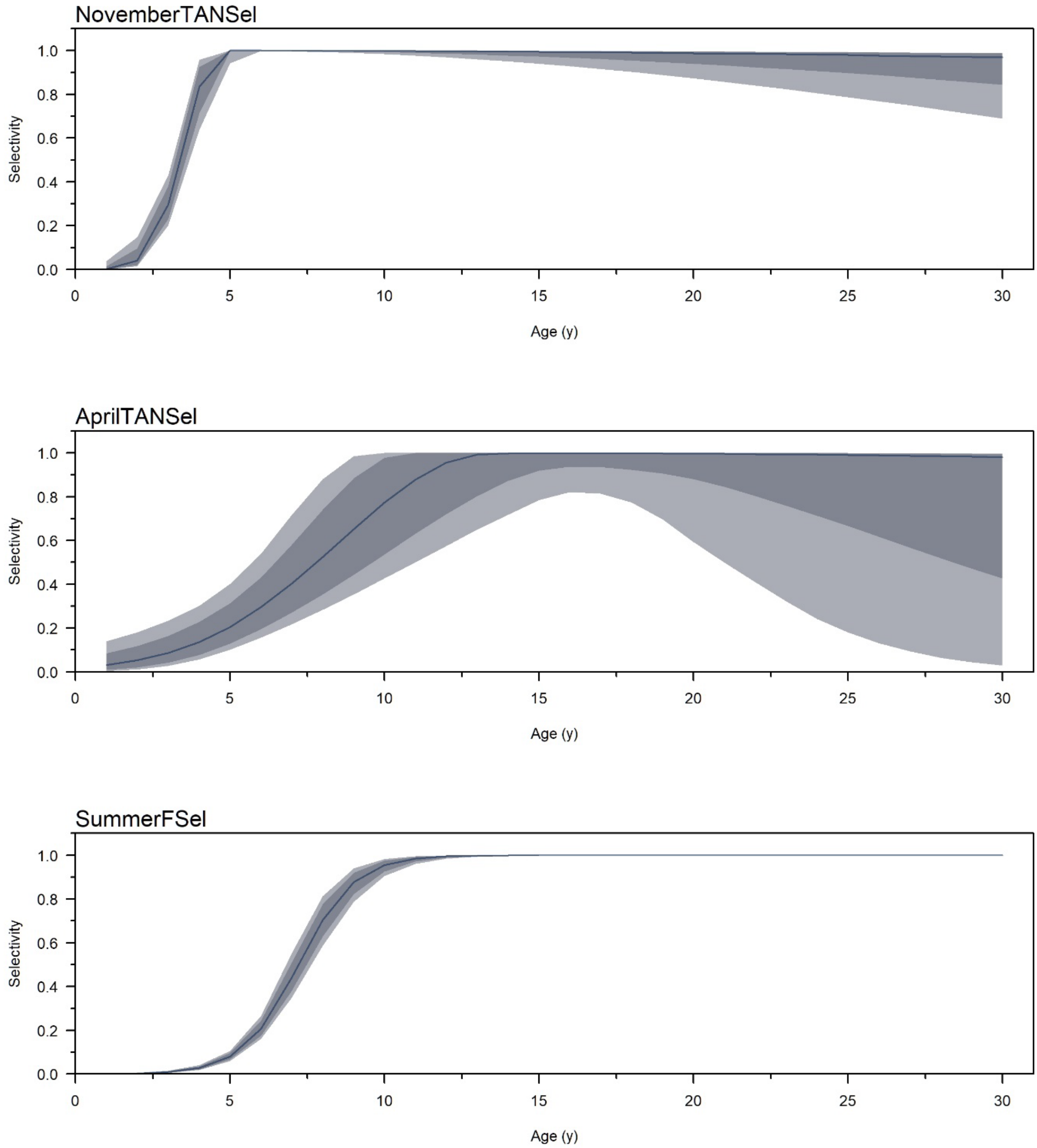


Figure 21: Base case model posterior distributions of the expected values for (top) November, (middle) April–May, and (bottom) commercial catch selectivities. The blue line indicates the median trajectory, the dark shaded area indicates the 80% credible interval, and the light shaded area indicates the 95% credible interval.

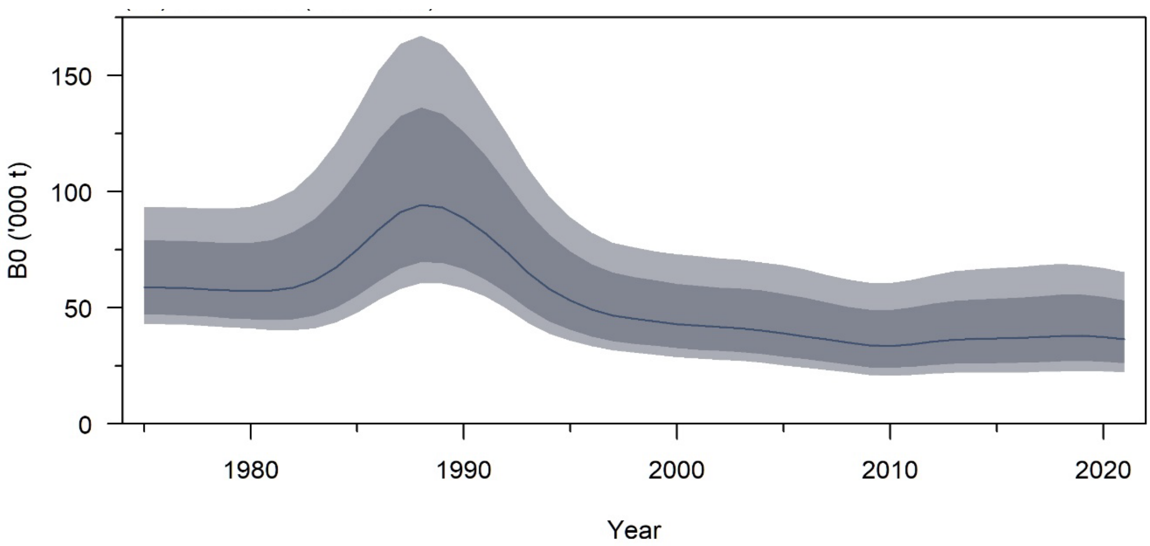


Figure 22: Posterior distribution of the historical (1975–2021) stock biomass (t) for the base case model for Sub-Antarctic hake. The blue line indicates the median trajectory, the dark shaded area indicates the 80% credible interval, and the light shaded area indicates the 95% credible interval.

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 target trawl fishery within the New Zealand EEZ were estimated by Anderson et al. (2019) as 0.42%.

The potential for incidental mortality of small hake associated with escapement through the net mesh was investigated by comparing the spatial distribution of fishing effort in relation to the spatial availability of small hake. Hake smaller than 40 cm in length were only caught in a few localised areas of the Sub-Antarctic (Figure 23) and, when observed, represented typically less than 2% of the catch.

Given the low proportions of likely under-reporting or additional mortality 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. 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 24).

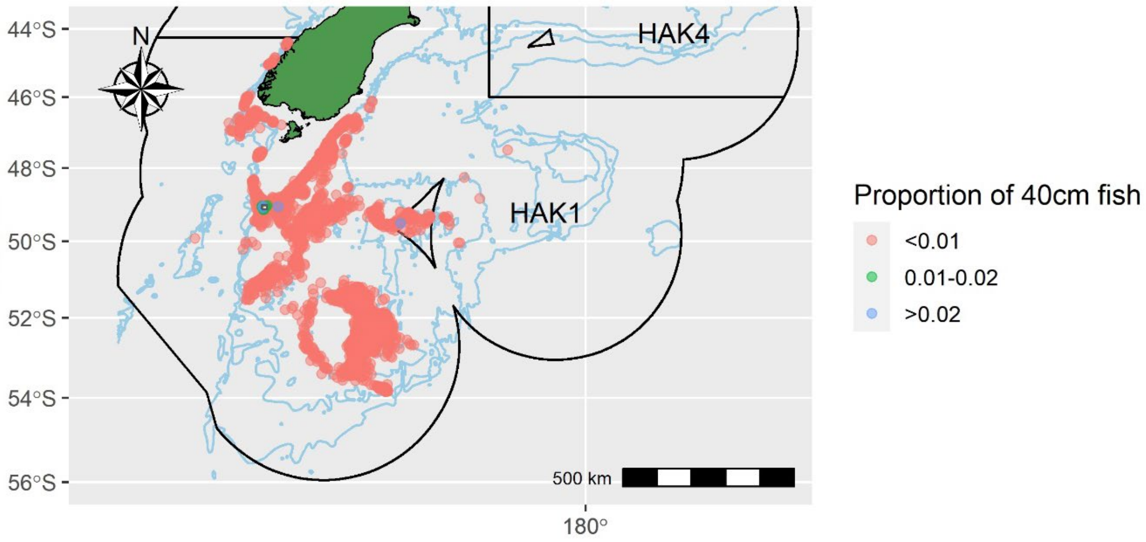


Figure 23: Proportion of small hake (< 40 cm) observed in Observer length measurements in the Sub-Antarctic, 1990–2020.

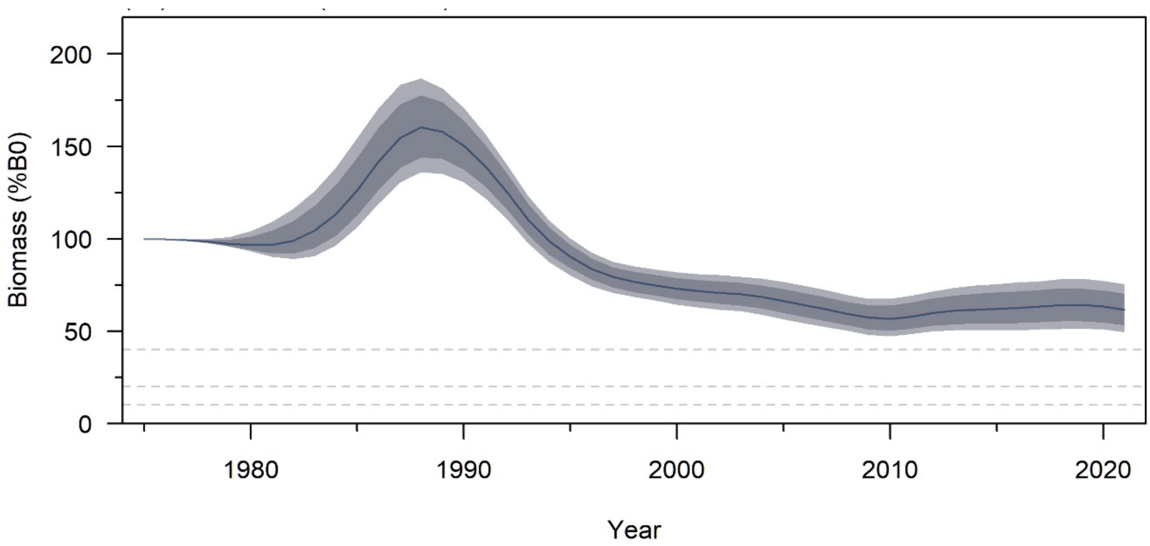


Figure 24: The base+ MCMC stock status trajectory (% B_0) for 1974–2021. The blue line indicates the median trajectory, the dark shaded area indicates the 80% credible interval, and the light shaded area indicates the 95% credible interval. Dotted horizontal lines indicate the target (40% B_0), and soft (20% B_0), and hard (10% B_0) limits 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 (1066 t) or the current TACC for all of HAK 1 (3701 t). The catch split between summer and winter was based on the average catch split for the most recent five years of reported catches (2016–2020).

Results are shown in Table 13 for the estimated stock status, and in Table 14 for risks of being below target, soft, or hard limits. Figure 25 shows the *SSB* trajectories under the assumption of current catch and recent year class strengths projected for five years into the future, and Figure 26 shows the same projection as percent of B_0. Stock status in 2026 is expected to remain fairly stable or even increase slightly over the next five years under assumptions of current catch but decline if catches were at the current level of the HAK 1 TACC. Only with catches equal to the current HAK 1 TACC, and for the sensitivities with low *M*, or when the model was fitted to CPUE, was the probability of stock biomass falling below 40% B_0 equal to or higher than 50%.

Table 13: Estimates of B_0 (t) and 95% credible intervals for the estimated projected status (B_{2026} as a percent of B_0) for 2022–2026 for the base case and selected sensitivity models for Sub-Antarctic 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 (1066 t) or the TACC (3701 t). YCS is year class strength.

Assumption	Model	B_0	B_{2022}	B_{2023}	B_{2024}	B_{2025}	B_{2026}
All YCS with current catch	2021 base	59 210	47.9–74.8	46.7–78.7	46.2–88.4	46.3–100.2	46.1–111.2
	(e) CPUE CV2	53 400	40.5–60.9	39.7–67.7	39.3–81.3	39.0–93.6	39.7–103.2
	(h) Fixed *M* 0.15	40 440	39.7–63.7	39.3–64.4	39.0–68.5	39.0–74.1	39.1–80.7
	(i) Fixed *M* 0.19	54 000	48.1–74.6	47.3–77.3	46.5–85.0	45.7–95.5	46.0–104.4
	(j) Fixed *M* 0.23	75 130	53.2–84.9	51.5–89.5	51.1–100.1	51.4–111.6	51.5–121.0
Recent YCS with current catch	2021 base	59 210	47.2–73.7	45.1–73.9	43.8–74.8	42.5–76.4	41.9–78.1
	(e) CPUE CV2	53 400	39.8–58.7	38.1–59.4	36.5–61.0	35.4–62.6	34.2–63.9
	(h) Fixed *M* 0.15	40 440	39.3–63.5	38.2–63.5	37.3–64.8	36.5–66.4	35.4–68.3
	(i) Fixed *M* 0.19	54 000	47.5–73.3	45.9–73.4	44.4–74.6	42.9–76.1	41.4–77.9
	(j) Fixed *M* 0.23	75 130	52.1–83.8	50.3–85.0	48.4–87.1	46.9–89.4	46.0–91.5
All YCS with TACC	2021 base	59 210	45.7–73.4	40.2–73.6	36.1–81.3	32.7–90.4	30.0–97.5
	(e) CPUE CV2	53 400	38.3–59.3	33.0–62.5	28.6–73.7	25.1–82.2	22.5–89.9
	(h) Fixed *M* 0.15	40 440	36.8–61.2	30.4–57.0	24.6–56.2	19.6–57.1	15.3–58.6
	(i) Fixed *M* 0.19	54 000	46.0–72.9	40.6–72.1	35.6–76.7	31.7–83.8	29.2–89.4
	(j) Fixed *M* 0.23	75 130	51.7–83.8	47.0–85.7	43.8–94.6	41.7–103.5	39.9–111.0
Recent YCS with TACC	2021 base	59 210	44.9–72.2	38.6–69.3	33.3–67.7	28.7–66.8	25.2–66.3
	(e) CPUE CV2	53 400	37.4–57.1	31.3–54.7	25.4–53.0	20.7–51.2	16.6–49.4
	(h) Fixed *M* 0.15	40 440	36.4–61.1	29.3–56.1	22.8–52.6	16.9–49.8	11.8–47.4
	(i) Fixed *M* 0.19	54 000	45.3–71.6	39.3–68.3	33.9–66.1	29.0–64.8	24.6–63.4
	(j) Fixed *M* 0.23	75 130	50.6–82.6	45.8–81.1	40.9–80.9	37.3–81.2	34.3–81.8

Table 14: Estimated projected probability of being below the target (40% B_0) or the soft or hard limits (20% or 10% B_0 respectively) for 2021 and 2026, for the base case and selected sensitivity models for Sub-Antarctic 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 (1066.4 t) or the TACC (3701 t). YCS is year class strength.

Assumption	Model	Probability B_{2021}			Probability B_{2026}		
		<40%	<20%	<10%	<40%	<20%	<10%
All YCS with current catch	2021 base	0.00	0.00	0.00	0.00	0.00	0.00
	(e) CPUE CV2	0.01	0.00	0.00	0.03	0.00	0.00
	(h) Fixed *M* 0.15	0.02	0.00	0.00	0.04	0.00	0.00
	(i) Fixed *M* 0.19	0.00	0.00	0.00	0.00	0.00	0.00
	(j) Fixed *M* 0.23	0.00	0.00	0.00	0.00	0.00	0.00
Recent YCS with current catch	2021 base	0.00	0.00	0.00	0.01	0.00	0.00
	(e) CPUE CV2	0.01	0.00	0.00	0.16	0.00	0.00
	(h) Fixed *M* 0.15	0.02	0.00	0.00	0.10	0.00	0.00
	(i) Fixed *M* 0.19	0.00	0.00	0.00	0.02	0.00	0.00
	(j) Fixed *M* 0.23	0.00	0.00	0.00	0.00	0.00	0.00
All YCS with TACC	2021 base	0.00	0.00	0.00	0.18	0.00	0.00
	(e) CPUE CV2	0.01	0.00	0.00	0.50	0.01	0.00
	(h) Fixed *M* 0.15	0.02	0.00	0.00	0.79	0.08	0.00
	(i) Fixed *M* 0.19	0.00	0.00	0.00	0.24	0.00	0.00
	(j) Fixed *M* 0.23	0.00	0.00	0.00	0.03	0.00	0.00
Recent YCS with TACC	2021 base	0.00	0.00	0.00	0.34	0.01	0.00
	(e) CPUE CV2	0.01	0.00	0.00	0.85	0.06	0.00
	(h) Fixed *M* 0.15	0.02	0.00	0.00	0.90	0.18	0.01
	(i) Fixed *M* 0.19	0.00	0.00	0.00	0.41	0.01	0.00
	(j) Fixed *M* 0.23	0.00	0.00	0.00	0.08	0.00	0.00

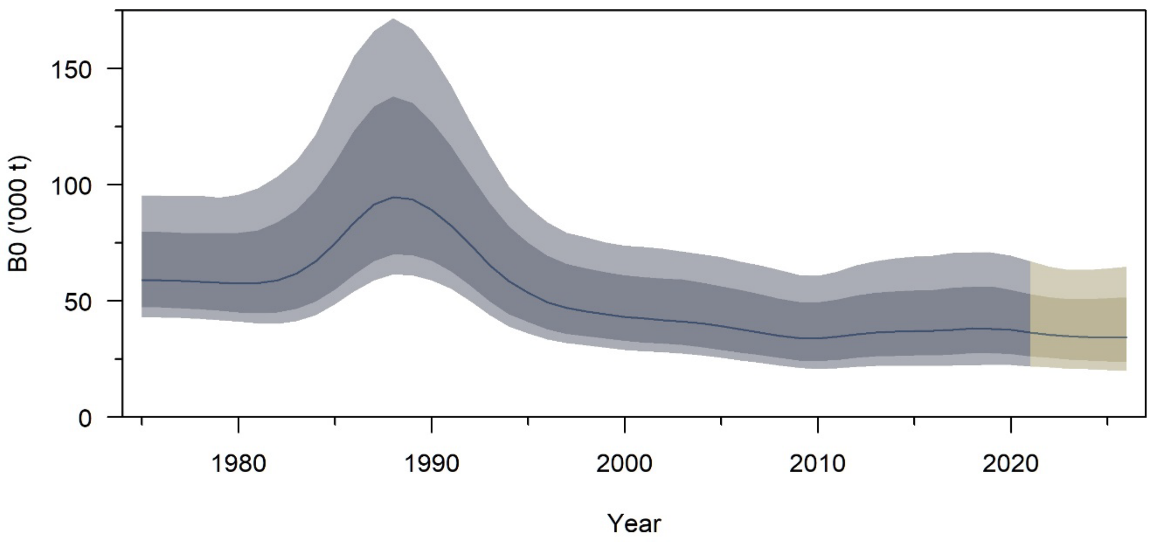


Figure 25: Posterior distribution of the historical (1975–2021, grey) and projected (2022–2026, olive) stock biomass for the base case model for Sub-Antarctic hake. The blue line indicates the median trajectory, the dark shaded area indicates the 80% credible interval, and the light shaded area indicates the 95% credible interval.

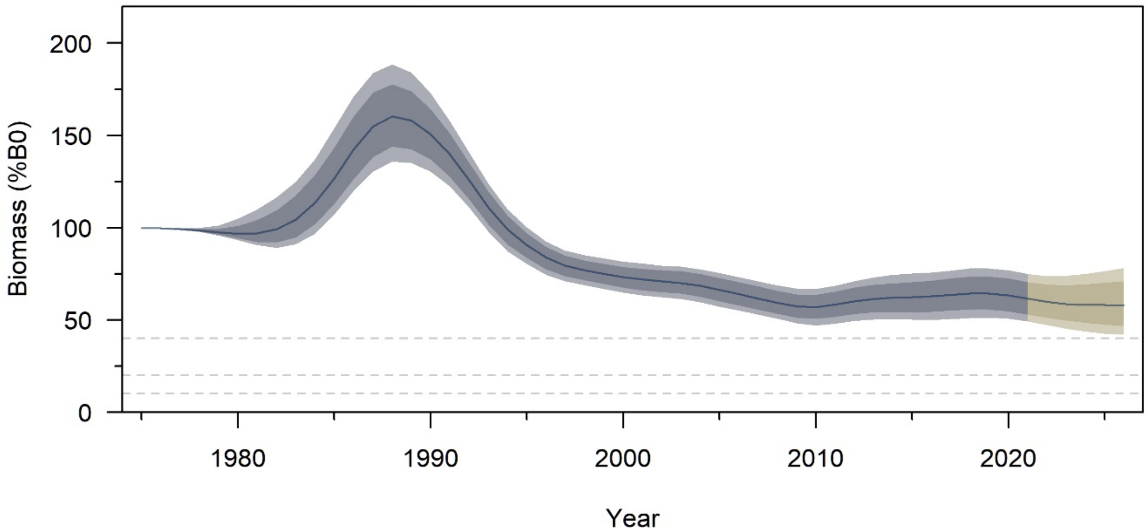


Figure 26: Posterior distributions of the historical (1975–2021, grey) and projected (2022–2026, olive) stock biomass as a percent of B_0 for the base case model for Sub-Antarctic hake. The blue line indicates the median trajectory, the dark shaded are indicates the 80% credible interval, and the light shaded area indicates the 95% credible interval. Dotted horizontal lines indicate the target (40% B_0), and soft (20% B_0), and hard (10% B_0) limits, 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 2021 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 27 shows the trajectory from the base case model of the total number of 1+ aged fish in the population over the period 1975–2021. This suggests that the current number of fish in the population is at about 85% (95% credible interval 64–101%) of the initial total abundance. Figure 28 shows the biomass trajectory of the immature 1+ aged biomass from the population over the period 1975–2021. This suggests that the current biomass of immature fish in the population is at about 78% (95% credible interval 65–96%) of the initial total biomass of immature fish.

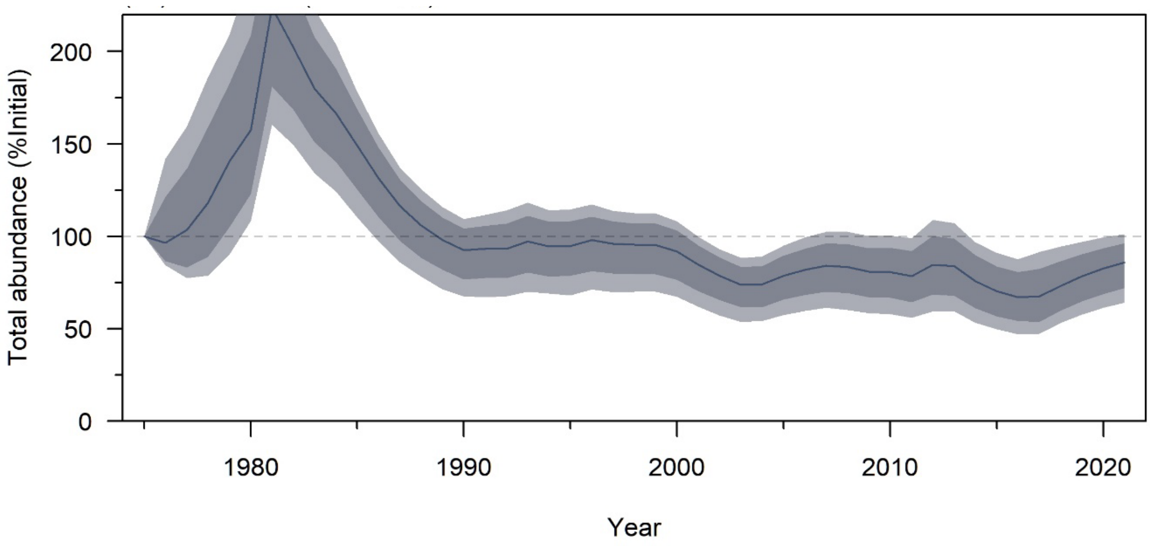


Figure 27: The base case model posterior distribution of the total abundance (number) of immature and mature hake (%Initial) for 1974–2021. The blue line indicates the trajectory of the initial total abundance, the dark shaded area indicates the 80% credible interval, and the light shaded area indicates the 95% credible interval. Dotted horizontal lines indicate the target (40% B_0), and soft (20% B_0), and hard (10% B_0) limits, respectively.

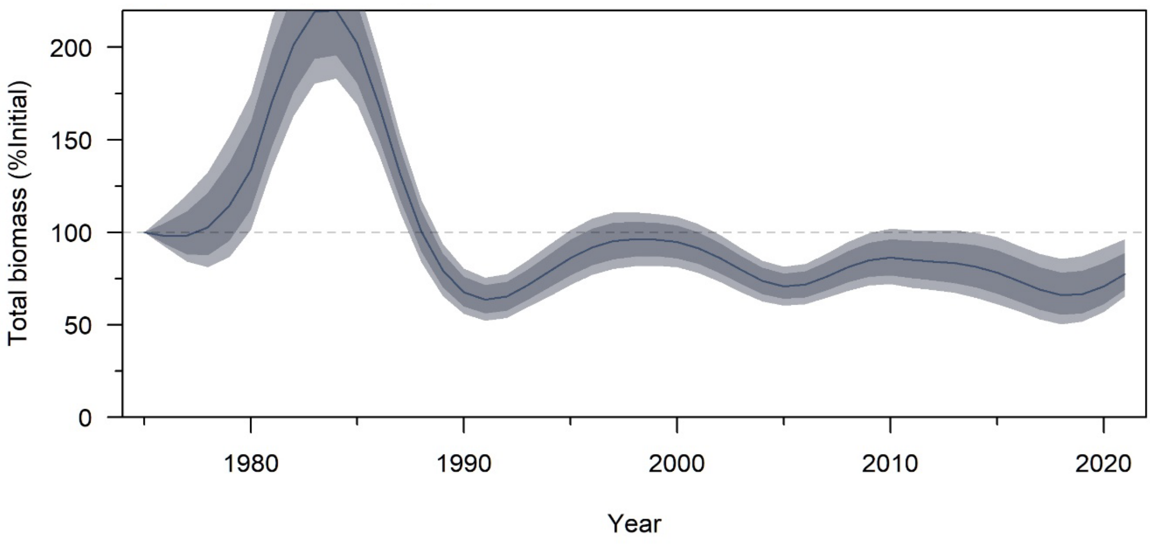


Figure 28: The base case model posterior distribution of the total biomass of immature hake (%Initial) for 1974–2021. The blue line indicates the trajectory of the initial total abundance, the dark shaded area indicates the 80% credible interval, and the light shaded area indicates the 95% credible interval. Dotted horizontal lines indicate the target (40% B_0), and soft (20% B_0), and hard (10% B_0) limits, respectively.

4. DISCUSSION

The initial stock assessment model for Sub-Antarctic hake in HAK 1 presented here was developed from the 2018 assessment (Dunn 2019). The stock assessment by Dunn (2019) concluded that the Sub-Antarctic spawning stock had been reduced to 50% of the pre-exploitation biomass (B_0), above the management target of 40% B_0, and that at current catch levels (about 1400 t) the stock was likely to fluctuate around current levels.

This assessment updated the previous model with new observations made since the 2018 assessment, revised the annual cycle, updated the CPUE indices, and corrected the time series of the November biomass indices. This assessment suggested that recent year classes were not as weak as had previously been estimated and that the current stock status was consequently slightly higher.

The 2020 plenary for Sub-Antarctic hake (Fisheries New Zealand 2020) noted a number of major sources of uncertainty in previous assessments of Sub-Antarctic hake. That report noted that the summer trawl survey series had shown a decline over time. However, once the time series had been corrected in recent years, the decline was not as apparent and was more consistent with the trend in the CPUE indices. There remains a lack of contrast in this series (the main relative abundance series) which makes it difficult to accurately estimate the upper bound of the current biomass.

The assumption that the Sub-Antarctic 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, the association of Puysegur hake with the Sub-Antarctic 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 in the Sub-Antarctic would remain relatively stable, and only projections with recent (lower) year class strengths at a level of the TACC for HAK 1 would result in a decline, albeit slowly, towards the target biomass of 40% B_0 over the next five years.

5. MANAGEMENT IMPLICATIONS

Reference points for hake in the Sub-Antarctic 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 0.17 using the base case model using the CAY calculation method of CASAL (Bull et al. 2012). B_{2021} 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 29).

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.

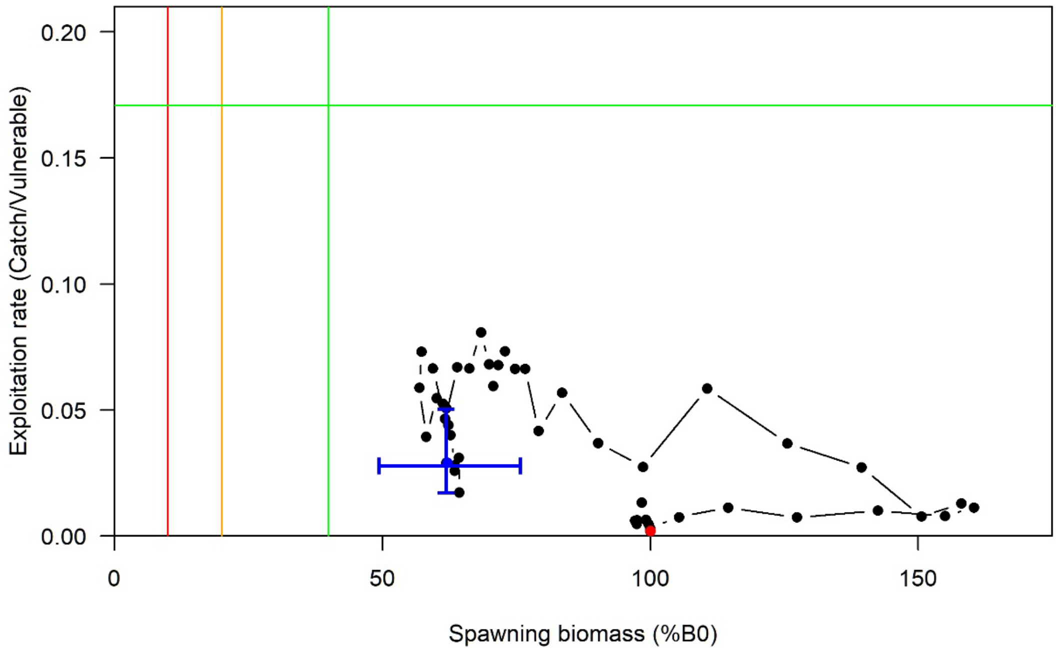


Figure 29: Trajectory over time of exploitation rate (*U*) and spawning biomass (% B_0), for the base case model from the start of the assessment period in 1975 (represented by a red point), to 2021 (in blue). The red vertical line at 10% B_0 represents the hard limit, the orange line at 20% B_0 is the soft limit, and green lines are the % B_0 target (40% B_0) and the corresponding exploitation rate (U_{40} = 0.17 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 2021.

6. ACKNOWLEDGEMENTS

We thank the Fisheries New Zealand Data Management Team for the data extracts used in these analyses and the additional assistance and information on interpretation. Dave Foster (Fisheries New Zealand Deepwater Management Team) provided supplementary data on vessel meal plants. We also thank Sira Ballara, Matt Dunn, David Middleton, Adam Langley, Andy Smith, and Jack Fenaughty for comments and advice, as well as the members of the Deepwater Working Group for their input and discussions of this work. This report was funded by the Fisheries New Zealand under project HAK 2020-01.

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.

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.

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. (Unpublished Final Research Report for Ministry of Fisheries Project HAK2003-01, held by Fisheries New Zealand, Wellington.) 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. (2021). 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 Report 2021/74*. 52 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.

Fisheries New Zealand (2020). Report from the Fishery Assessment Plenary, May 2020: stock assessments and stock status. Compiled by the Fisheries Science and Information Group, Fisheries New Zealand. 1746 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, London.

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

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*. 46 p.

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. N*ew 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.; 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 Research Document 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.

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.