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Stock assessment of hake (*Merluccius australis*) on Chatham Rise for the 2019–20 fishing year

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Holmes, S.J. (2021). Stock assessment of hake (*Merluccius australis*) on Chatham Rise for the 2019–20 fishing year.

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This report summarises the stock assessment for the 2019–20 fishing year of the hake stock found on Chatham Rise (Quota Management Area HAK 4 and part of HAK 1). An updated assessment was conducted using the general-purpose Bayesian stock assessment program CASAL v2.30. The assessment incorporated all relevant biological parameters, the commercial catch history, updated CPUE series, updated research trawl biomass index, and series of proportion-at-age data from the commercial trawl fisheries and research surveys. The analysis included fishery data up to the end of the 2018–19 fishing year.

The stock assessment model was updated and assumed a single sex (sex not in the partition), with the primary concern being the fit of the model to the summer (January) research trawl survey series. The January trawl survey series showed evidence of a decline in biomass from 1992 to about 2005. The assessment produced estimates of the hake Chatham Rise stock status consistent with previous assessments. The stock was steadily fished down throughout the 1990s, but in years since 2006 spawning biomass has slowly recovered and B_{2020} was estimated to be 55% of B_0. Strong year classes were estimated to have spawned in 2001 and 2010 (age 1 in 2002 and 2011), in contrast to generally poor spawning success in other years from 1995 to 2017, and resulted in a recent stock biomass rebuild. A sensitivity model run incorporating a CPUE series as an additional biomass index gave a slightly more optimistic estimate of stock status (B_{2020} was 58% of B_0).

Projections of stock status under constant future catch levels were made to the end of the 2024–25 fishing year. Catches at the average level of those from the last 6 years (362 t) would allow further biomass rebuilding if average levels of recruitment seen throughout the assessment history continued. If one or more factors limited recruitment to a lower average level, as seen over the last 10 years, then catches at the recent average level (362 t) were estimated to maintain the stock at its current status. An annual catch equal to 1800 t (the HAK 4 TACC) over the next five years was estimated to reduce the Chatham Rise stock status to approximately 40% B_0.

1. INTRODUCTION

This report outlines the stock assessment of the hake (*Merluccius australis*) stock on the Chatham Rise (Quota Management Area (QMA) HAK 4 and part of HAK 1) with the inclusion of data up to the end of the 2018–19 fishing year. The current stock hypothesis for hake suggests that there are three separate hake stocks (Colman 1998); the west coast South Island stock (WCSI, the area of HAK 7 off the west coast South Island), the Sub-Antarctic stock (the area of HAK 1 that encompasses the Southern Plateau), and the Chatham Rise stock (HAK 4 and the area of HAK 1 on the western Chatham Rise).

The stock assessment of hake on Chatham Rise is presented as a Bayesian assessment implemented as a single stock model using the general-purpose stock assessment program CASAL v2.30 (Bull et al. 2012). Estimates of the current stock status and projected stock status are provided.

This report fulfils the objectives of Project HAK201901 "To complete a stock assessment of the Chatham Rise hake stocks including estimating biomass, sustainable yields, and status of the stock, and projecting biomass and stock status trajectories as required to support management", funded by Fisheries New Zealand. Revised catch histories for the Chatham Rise hake stock are reported here, as are the new model input data and research results.

1.1 Description of the fishery

Hake are widely distributed throughout the middle depths of the New Zealand Exclusive Economic Zone (EEZ) mostly south of latitude 40° S (Anderson et al. 1998). Adults are mainly distributed in depths from 250 to 800 m although some have been found as deep as 1200 m, whereas juveniles (age 0+) are found in shallower inshore regions under 250 m (Hurst et al. 2000). Hake are taken almost exclusively by trawl, and predominantly by large demersal trawlers — often as bycatch in fisheries targeting other species such as hoki (*Macruronus novaezelandiae*) and southern blue whiting (*Micromesistius australis*), although target fisheries also exist (Devine 2009, Ballara 2017). There is a small reported catch of hake from the bottom longline fishery targeting ling. Present management divides the fishery into three main fish stocks: (a) the Challenger QMA (HAK 7), (b) the Southeast (Chatham Rise) QMA (HAK 4), and (c) the remainder of the EEZ comprising the Auckland, Central, Southeast (Coast), Southland, and Sub-Antarctic QMAs (HAK 1). An administrative fish stock exists in the Kermadec QMA (HAK 10) although there are no recorded landings from this area. The hake QMAs are shown in Figure 1.

The largest fishery for hake has been off the west coast of the South Island (HAK 7). The Chatham Rise fishery ranks third behind the HAK 7 and Sub-Antarctic (HAK 1) fisheries. In all three areas hake have been caught mainly as bycatch by trawlers targeting hoki, although significant targeting occurs in both the Chatham Rise and Sub-Antarctic areas (Ballara 2013, 2015). In 2018–19, the TACCs for the QMAs were 2272 t HAK 7, 3701 t HAK 1, 1800 t HAK 4, and a nominal 10 t HAK 10, for a total for the EEZ of 10 575 t (Fisheries New Zealand 2020).

Increases in TACCs from 1000 t to 3500 t in HAK 4 from the 1991–92 fishing year allowed the fleet to increase the landings of hake from this fish stock. Over several years reported catches rose to the level of the new TACC. Landings from HAK 4 declined erratically from over 3000 t in 1998–99 to a low of 161 t in 2011–12. From 2004–05, the TACC for HAK 4 was reduced from 3500 t to 1800 t. Annual landings have been markedly lower than the new TACC since then, and lower than 300 t in all but one year since 2009–10.

Dunn (2003a) found that area misreporting between the WCSI and the Chatham Rise fisheries occurred from 1994–95 to 2000–01. He estimated that between 16 and 23% (700–1000 t annually) of WCSI landings were misreported as deriving from Chatham Rise, predominantly in June, July, and September. Levels of misreporting before 1994–95 and after 2000–01, and between WCSI and Sub-Antarctic, were estimated as negligible, and there is no evidence of significant misreporting since (Ballara 2013).

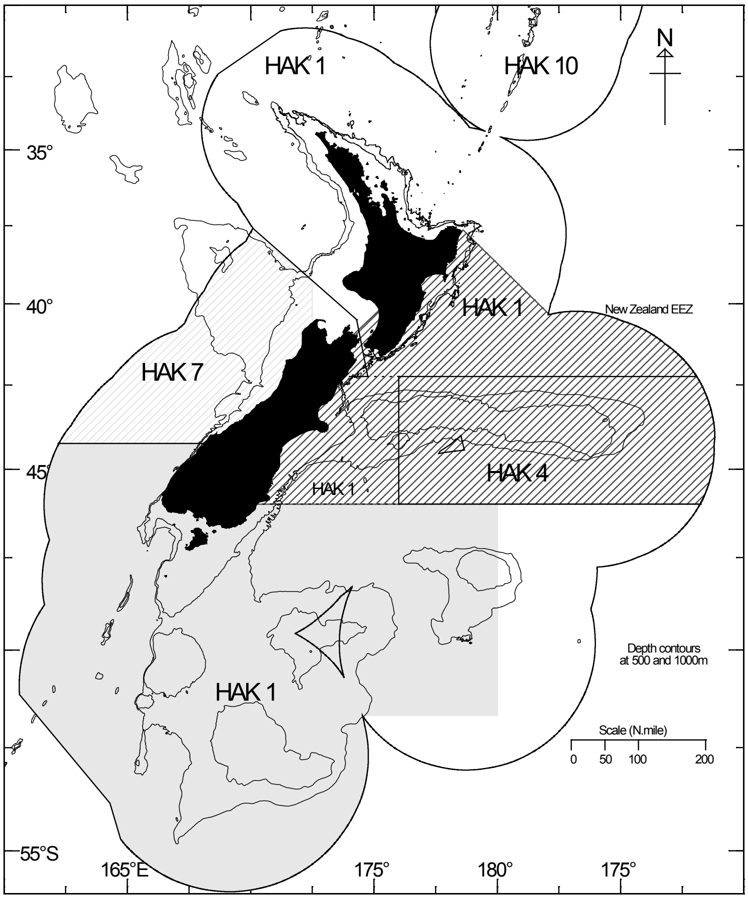

Figure 1: Quota Management Areas (QMAs) HAK 1, 4, 7, & 10; and the west coast South Island (light shading), Chatham Rise (dark shading), and Sub-Antarctic (grey) hake stock boundaries assumed in this report.

1.2 Literature review

Previous assessments of hake, by fishing year, are as follows: 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 2003b), 2003–04 (Dunn 2004a, 2004b), 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), 2016–17 (Horn 2017), 2017–18 (Dunn 2019) and 2018–19 (Kienzle et al. 2019). The Bayesian stock assessment software CASAL (Bull et al. 2012) has been used for all assessments since 2002–03. The most recent assessments by stock were: Chatham Rise (Horn 2017), Sub-Antarctic (Dunn 2019), and WCSI (Kienzle et al. 2019).

Since 1991, resource surveys have been carried out from R.V. *Tangaroa* in the Sub-Antarctic in November–December 1991–1993, 2000–2009, 2011, 2012, 2014, 2016, and 2018; September–October 1992, and April–June 1992, 1993, 1996, and 1998. On Chatham Rise, a consistent time series of resource surveys from *Tangaroa* has been carried out in January 1992–2014, 2016, 2018, and 2020. Appendix A gives more details about the surveys.

Standardised CPUE indices were updated to the 2010–11 fishing year for the WCSI and Chatham Rise stocks only by Ballara (2013), and for the Sub-Antarctic stock only to the 2012–13 fishing year by Ballara (2015). The latter document includes a descriptive analysis of all New Zealand's hake fisheries up to the 2012–13 fishing year. An updated descriptive analysis of all stocks to 2015–16, and CPUE for WCSI and Chatham Rise only, was completed by Ballara (2017). The most recent characterisations and CPUE indices are: Chatham Rise (McGregor in press), Sub-Antarctic (Ballara 2018), and WCSI (Finucci 2019).

A book on hakes of the world includes a chapter on the biology and fisheries of *Merluccius australis* in New Zealand waters (Horn 2015).

2. BIOLOGY, STOCK STRUCTURE, AND ABUNDANCE INDICES

2.1 Biology

Data collected by observers on commercial trawlers and from resource surveys suggest that there are at least three main spawning areas for hake (Colman 1998). Areas of relevance to the HAK 4 assessment are to the west of the Chatham Islands during a prolonged period from at least September to January and near the Mernoo Bank on the western Chatham Rise where spawning fish have been recorded occasionally. Other spawning areas are off the west coast of the South Island, where the season can extend from June to October, possibly with a peak in September and on the Campbell Plateau, primarily to the northeast of the Auckland Islands, from September to February with a peak in September–October. Spawning fish have also been recorded occasionally on the Puysegur Bank, with a seasonality that appears similar to that on the Campbell Plateau (Colman 1998).

Horn (1997) validated the use of otoliths to age hake. New Zealand hake reach a maximum age of at least 25 years. Males, which rarely exceed 100 cm total length, do not grow as large as females, which can grow to 120 cm total length or more. Readings of otoliths from hake have been used as age-length keys to scale up length frequency distributions for hake collected on resource surveys and from commercial fisheries on the Chatham Rise, Sub-Antarctic, and west coast South Island. The resulting age frequency distributions were reported by Horn & Sutton (2019).

Colman (1998) found that hake reach sexual maturity between 6 and 10 years of age, at total lengths of about 67–75 cm (males) and 75–85 cm (females); he concluded that hake reached 50% maturity at between 6 and 8 years in HAK 1, and 7–8 years in HAK 4. In assessments before 2005, the maturity ogive for the Chatham Rise and Sub-Antarctic was assumed from a combination of the estimates of Colman (1998) and model fits to the west coast South Island data presented by Dunn (1998).

From 2005 to 2007, maturity ogives for the Chatham Rise and Sub-Antarctic stocks were fitted within the assessment model to data derived from resource survey samples, including information on the gonosomatic index (GSI, the ratio of the gonad weight to body weight), gonad stage, and age (Horn & Dunn 2007, Horn 2008). Individual hake were classified as either immature or mature at sex and age, where maturity was determined from the gonad stage and gonosomatic index. Fish identified as stage 1 were classified as immature. Stage 2 fish were classified as immature or mature depending on the GSI index, using the definitions of Colman (1998) — i.e., classified as immature if GSI < 0.005 (males) or GSI < 0.015 (females), or mature if GSI ≥ 0.005 (males) or GSI ≥ 0.015 (females). Fish identified as stages 3–7 were classified as mature. From 2009 to 2011, fixed ogives as derived from the previously described model fitting procedure were used in the assessment models. In 2012, fixed ogives for all stocks were updated by fitting a logistic curve (from Bull et al. 2012) to the proportion mature at age data, by sex, with the fish classified as mature or immature as described above (Horn 2013b). The analysed data were derived from resource surveys over the following periods corresponding with likely spawning activity: Sub-Antarctic, October–February; Chatham Rise, November–January; WCSI, July–September. The proportions mature are listed in Table 1; values for combined sexes maturity were taken as the mean of the male and female values. Chatham Rise hake reach 50% maturity at about 5.5 years for males and 7 years for females.

For assessments up to 2008, length and age were related using the von Bertalanffy growth model (Horn 2008). Plots of the fitted curves on the raw data indicated that the von Bertalanffy model tended to underestimate the age of large fish. Consequently, the growth model of Schnute (1981) was fitted to the data sets (Table 1). This model appeared to better describe the growth of larger hake (Horn 2008), and the resulting parameters can be used in the CASAL stock assessment software. Most aged hake have been 3 years or older. However, younger juvenile hake have been taken in coastal waters off the east and west coasts of the South Island and on the Campbell Plateau. It is known that hake reach a total length of about 15–20 cm at 1 year old, and about 35 cm total length at 2 years (Horn 1997).

Estimates of natural mortality rate (*M*) and the associated methodology were given by Dunn et al. (2000); *M* was estimated as 0.18 y^{-1} for females and 0.20 y^{-1} for males. Colman et al. (1991) estimated *M* as 0.20 y^{-1} for females and 0.22 y^{-1} for males using the maximum age method of Hoenig (1983) (where they defined the maximum ages at which 1% of the population survives in an unexploited stock as 23 years for females and 21 years for males). These are similar to the values proposed by Horn (1997), who determined the age of hake by counting zones in sectioned otoliths and concluded from that study that it was likely that *M* was in the range 0.20–0.25 y^{-1}. Up to 2011, constant values of *M* were used in stock assessment models (i.e., 0.18 y^{-1} for females and 0.20 y^{-1} for males, or 0.19 y^{-1} for sexes combined), see Table 1. However, because true *M* is likely to vary with age, the assessments in 2012 (Sub-Antarctic, Horn 2013a) and 2013 (Chatham Rise and WCSI, Horn 2013b) allowed the estimation of age-dependent ogives for *M* within the models. The assessment reported below returned to using a fixed value for *M* as detailed in Table 1, but sensitivity runs tested the effect of imposing higher and lower values for *M* (0.15 and 0.23 respectively for sexes combined).

Table 1: Estimates of biological parameters for the Chatham Rise hake stock.

		Estimate				Source
Natural mortality						
	Males	$M = 0.20$				(Dunn et al. 2000)
	Females	$M = 0.18$				(Dunn et al. 2000)
	Both sexes	$M = 0.19$				
Weight = a·(length)^b (Weight in t, length in cm)						
Chatham Rise	Males	$a = 2.56 \times 10^{-9}$	$b = 3.228$			(Horn 2013a)
	Females	$a = 1.88 \times 10^{-9}$	$b = 3.305$			(Horn 2013a)
	Both sexes	$a = 2.00 \times 10^{-9}$	$b = 3.288$			(Horn 2013a)
von Bertalanffy growth parameters						
Chatham Rise	Males	$k = 0.330$	$t_0 = 0.09$	$L_\infty = 85.3$		(Horn 2008)
	Females	$k = 0.229$	$t_0 = 0.01$	$L_\infty = 106.5$		(Horn 2008)
Schnute growth parameters ($\tau_1 = 1$ and $\tau_2 = 20$ for all stocks)						
Chatham Rise	Males	$y_1 = 24.6$	$y_2 = 90.1$	$a = 0.184$	$b = 1.742$	(Horn 2008)
	Females	$y_1 = 24.4$	$y_2 = 114.5$	$a = 0.098$	$b = 1.764$	(Horn 2008)
	Both sexes	$y_1 = 24.5$	$y_2 = 104.8$	$a = 0.131$	$b = 1.700$	(Horn & Francis 2010)

Maturity ogives (proportion mature at age)

	Age	2	3	4	5	6	7	8	9	10	11	12	13
Chatham	Males	0.02	0.07	0.20	0.44	0.72	0.89	0.96	0.99	1.00	1.00	1.00	1.00
	Females	0.01	0.02	0.06	0.14	0.28	0.50	0.72	0.86	0.94	0.98	0.99	1.00
	Both	0.02	0.05	0.13	0.29	0.50	0.70	0.84	0.93	0.97	0.99	0.99	1.00

Miscellaneous parameters

Steepness (Beverton & Holt stock-recruitment relationship)	0.84
Proportion spawning	1.0
Proportion of recruits that are male	0.5
Ageing error CV	0.08
Maximum exploitation rate (U_{max})	0.7

Dunn et al. (2010) found that the diet of hake on the Chatham Rise was dominated by teleost fishes, in particular Macrouridae. Macrouridae accounted for 44% of the prey weight and consisted of at least six species, of which javelinfish, *Lepidorhynchus denticulatus*, was most frequently identified. Hoki were less frequent prey but being relatively large accounted for 37% of prey weight. Squids were found in 7% of the stomachs and accounted for 5% of the prey weight. Crustacean prey consisted predominantly of natant decapods, with pasiphaeid prawns occurring in 19% of the stomachs. No hake were recorded in the diets of 25 other sympatric demersal species (M. Dunn, pers. comm.).

Length-weight relationships for hake from the Sub-Antarctic and Chatham Rise stocks were revised by Horn (2013a, 2013b) using all available length-weight data collected during trawl surveys since 1989, see Table 1.

2.2 Stock structure

There are at least three hake spawning areas: off the west coast of the South Island, on the Chatham Rise, and on the Campbell Plateau (Colman 1998). Juvenile hake are found in all three areas, there are differences in size frequency of hake between the west coast and other areas, and differences in growth parameters between all three areas (Horn 1997). There is reason, therefore, to believe that at least three separate stocks can be assumed for the EEZ.

Analysis of morphometric data (J.A. Colman, NIWA, unpublished data) showed little difference between hake from the Chatham Rise and from the east coast of the North Island, but highly significant differences between these fish and those from the Sub-Antarctic, Puysegur, and off the west coast. The Puysegur fish were most like those from the west coast South Island, although, depending on which variables were used, they could not always be distinguished from the Sub-Antarctic hake. However, the data were not unequivocal, so the stock affinity is uncertain.

For stock assessment models, the Chatham Rise stock was considered to include the whole of the Chatham Rise (HAK 4 and the western end of the Chatham Rise that forms part of the HAK 1 management area), as well as the southern portion of the east coast North Island. The stock areas assumed for this report are shown in Figure 1.

2.3 Resource surveys

The resource surveys carried out at depths of 200–800 m on the Chatham Rise annually from 1992 to 2014, then biennially, 2016, 2018 and 2020 by *Tangaroa* had the same gear and similar survey designs (see Appendix A). Although the survey designs since 1992 were similar, there was a reduction in the number of stations surveyed between 1996 and 1999, and some strata in the survey design used between 1996 and 1999 were merged (see Bull & Bagley 1999). The surveys since 2000 used a revised design, with some strata being split and additional stations added. Since 2000 some of the *Tangaroa* surveys included deep-water strata (i.e., 800–1300 m) on the Chatham Rise, although data from these strata were excluded from the present analysis to maintain consistency in the time series.

Chatham Rise surveys were conducted by *Shinkai Maru* (March 1983 and June–July 1986) and *Amaltal Explorer* (November–December 1989). However, these surveys used a range of gear, survey methodologies, and survey designs (Livingston et al. 2002) and cannot be used as a consistent time series. The biomass estimates from Chatham Rise resource surveys are shown in Table 2 with further details in Appendix A. Catch distributions from these surveys are plotted by Stevens et al. (2018).

Table 2: Research survey indices (and associated CVs) for the Chatham Rise stock. The indices relate to the core survey strata only, i.e. 200–800 m for Chatham Rise.

		Chatham Rise	
Year	Vessel	Biomass (t)	CV
1989	*Amaltal Explorer*	3 576	0.19
1992	*Tangaroa*	4 180	0.15
1993	*Tangaroa*	2 950	0.17
1994	*Tangaroa*	3 353	0.10
1995	*Tangaroa*	3 303	0.23
1996	*Tangaroa*	2 457	0.13
1997	*Tangaroa*	2 811	0.17
1998	*Tangaroa*	2 873	0.18
1999	*Tangaroa*	2 302	0.12
2000	*Tangaroa*	2 090	0.09
2001	*Tangaroa*	1 589	0.13
2002	*Tangaroa*	1 567	0.15
2003	*Tangaroa*	890	0.16
2004	*Tangaroa*	1 547	0.17
2005	*Tangaroa*	1 049	0.18
2006	*Tangaroa*	1 384	0.19
2007	*Tangaroa*	1 824	0.12
2008	*Tangaroa*	1 257	0.13
2009	*Tangaroa*	2 419	0.21
2010	*Tangaroa*	1 700	0.25
2011	*Tangaroa*	1 099	0.15
2012	*Tangaroa*	1 292	0.15
2013	*Tangaroa*	1 877	0.15
2014	*Tangaroa*	1 377	0.15
2015	No survey	–	
2016	*Tangaroa*	1 299	0.19
2017	No survey	–	
2018	*Tangaroa*	1 660	0.34
2019	No survey	–	
2020	*Tangaroa*	1 037	0.20

2.4 Observer age samples

The fishery on the Chatham Rise was stratified using a tree-based regression on mean lengths of hake in tows where observers had measured five or more hake (Horn & Dunn 2007). The defined strata are shown in Figure 2. Mean fish length tends to increase from west to east, and with increasing depth. Area 404 (equivalent to Statistical Area 404) includes a known spawning ground. However, Horn & Francis (2010) showed that the two western fisheries had similar age-frequency distributions, and the two eastern fisheries were data poor. Consequently, they used two strata, eastern and western, divided at 178.1° E. Observer data from each fishery stratum were converted into catch-at-age distributions if there were at least 400 length measurements (from western strata) or 320 length measurements (from eastern strata), and the mean weighted CV over all age classes was less than 30%. The available data (described by Horn & Sutton (2019)) were from almost all fishing years between 1991–92 and from 2015–16 (see also Table 4). The level of observer sampling on the Chatham Rise in all years after 2016 has been inadequate to produce useful age distributions (P. Horn, pers comm.)

Although the observer length data from each year were partitioned into fisheries (i.e., two strata in each of the two fisheries, as shown in Figure 2), the age data from each year were not (i.e., a single age-length key was constructed for each year and applied to the available sets of length data from that year).

Horn & Dunn (2007) showed that mean age at length did not differ between fisheries, so the use of a single age-length key per year should not bias the age distributions.

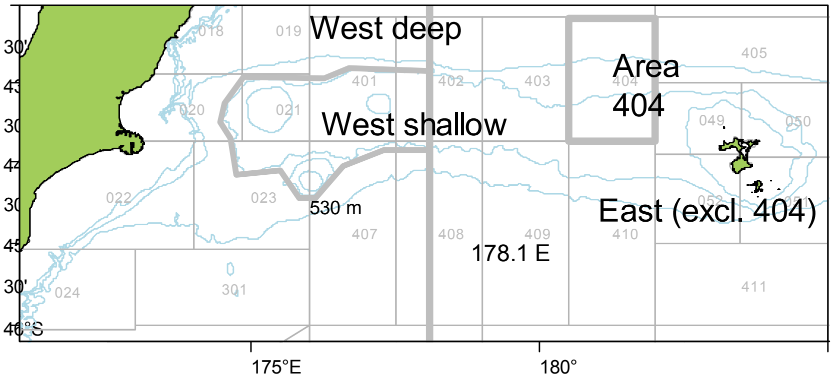

Figure 2: Fishery strata defined for the Chatham Rise hake fishery. Large numbers show longitudes or depths of fishery boundaries; small numbers denote statistical areas. The stratum boundary defined by depth (530 m) is shown only approximately. Isobaths at 1000, 500, and 250 m are also shown.

2.5 CPUE indices

CPUE series were produced for the Chatham Rise using data to the end of the 2018–19 fishing year (McGregor in press). CPUE series were produced for both the eastern and western fisheries on the Chatham Rise using Quota Management System data, also a 'whole Chatham Rise' index using data from both eastern and western fisheries. The eastern series was chosen by the Deepwater Working Group for inclusion in previous assessments (Horn 2013b, 2017). For the assessment described in this report, the series analysing the daily processed catch from the eastern fishery was selected for full sensitivity analysis (see Table 3); the western fishery and whole Chatham Rise series were considered in initial sensitivity runs but not considered further. The evolution of CPUE for the western fishery conflicted with both that from the survey and eastern fishery. The series for the whole Chatham Rise could be seen to represent a form of average between western and eastern fishery CPUEs. In these CPUE series, each annual index related to a fishing year as used in the assessment, i.e., although in general fishing year is defined as 1 October–30 September, fishing year for hake on the Chatham Rise is defined as 1 September–31 August due to the timing of spawning, therefore CPUE series were defined for 1 September–31 August.

Table 3: **Hake CPUE indices (and associated CVs) available to the Chatham Rise hake stock assessment (from McGregor in press).**

Fishing	Chatham east		Chatham west		Whole Chatham	
year	Index	CV	Index	CV	Index	CV
1989–90	2.26	0.26	0.93	0.11	1.28	0.09
1990–91	2.5	0.11	1.04	0.09	1.56	0.06
1991–92	1.57	0.1	0.95	0.07	1.32	0.05
1992–93	1.47	0.1	0.89	0.07	1.17	0.06
1993–94	1.94	0.13	1.04	0.09	1.31	0.07
1994–95	1.2	0.08	1.34	0.07	1.31	0.05
1995–96	1.1	0.1	1.41	0.06	1.28	0.05
1996–97	1.49	0.08	1.54	0.05	1.5	0.04
1997–98	1.16	0.07	1.28	0.04	1.2	0.03
1998–99	0.9	0.06	1.28	0.05	1.06	0.03
1999–00	1.17	0.07	1.37	0.05	1.29	0.04
2000–01	1.06	0.06	1.34	0.04	1.24	0.03
2001–02	0.82	0.08	1.11	0.05	1.02	0.04
2002–03	0.92	0.08	1.06	0.05	1.01	0.04
2003–04	0.97	0.07	0.98	0.07	1.04	0.04
2004–05	0.65	0.09	0.95	0.08	0.77	0.06
2005–06	0.89	0.12	1.12	0.08	1.02	0.06
2006–07	1.27	0.08	0.97	0.08	1.11	0.05
2007–08	0.91	0.08	0.96	0.08	0.9	0.05
2008–09	0.7	0.11	0.85	0.08	0.77	0.06
2009–10	0.64	0.11	0.79	0.07	0.77	0.06
2010–11	0.57	0.08	0.7	0.07	0.63	0.05
2011–12	0.48	0.11	0.71	0.09	0.59	0.06
2012–13	0.53	0.12	0.62	0.09	0.55	0.07
2013–14	0.8	0.1	0.63	0.1	0.71	0.07
2014–15	0.6	0.11	0.72	0.08	0.67	0.06
2015–16	0.86	0.11	0.9	0.09	0.86	0.06
2016–17	1.13	0.11	1.14	0.08	1.11	0.06
2017–18	1.12	0.07	1.13	0.07	1.08	0.05
2018–19	0.93	0.1	1.09	0.07	0.99	0.05

3. MODEL STRUCTURE, INPUTS, AND ESTIMATION

An updated assessment of the Chatham Rise stock is presented here. A summary of all input data series available is given in Table 4. Data used in the base case run are highlighted in bold.

As in previous assessments of this stock (Horn & Francis 2010, Horn 2011, 2013b, 2017), the assessment model partitioned the population into age groups 1–30, with the last age class considered a plus group. Sex was not in the partition. For Chatham Rise, the model's annual cycle was based on a year beginning on 1 September and divided the year into three steps (Table 5). The fishing year (starting 1 October) is not used in this assessment because peak landings tend to occur from September to January, so it is logical to include the September catch with landings from the five months immediately following it, rather than with catches taken about seven months previously (Horn & Francis 2010). Note that model references to 'year' within this document are labelled as the most recent calendar year, e.g., the year 1 September 1998 to 31 August 1999 for Chatham Rise is referred to as '1999'.

Table 4: **Summary of available model data inputs for the Chatham Rise hake assessment. Data used in the base case model are highlighted in bold.**

Data series	Years
Trawl survey proportion at age (*Tangaroa*, Jan)	**1992–2014, 2016, 2018, 2020**
Trawl survey biomass (*Tangaroa*, Jan)	**1992–2014, 2016, 2018, 2020**
CPUE (trawl, Chatham East)	1990–2019
CPUE (trawl, Chatham West)	1990–2019
CPUE (trawl, whole Chatham Rise)	1990–2019
Commercial trawl proportion-at-age (Chat observer data West) (all year); unsexed	**1992, 1994–2006, 2008-2011, 2014, 2016**
Commercial trawl proportion-at-age (Chat observer data East) (all year); unsexed	**1992, 1995, 1997-1998, 2001, 2004, 2007, 2015**

Table 5: **Annual cycle of the Chatham Rise stock model, showing the processes taking place at each time step, their sequence within each time step, and the available observations. Fishing and natural mortality that occur within a time step occur after all other processes, with half of the natural mortality for that time step occurring before and half after the fishing mortality.**

					Observations	
Chatham Rise						
Step	Period	Processes	M[1]	Age[2]	Description	%Z[3]
1	Sep–Feb	Fishing, recruitment, & spawning	0.42	0.25	January trawl survey	100
					CPUE[4]	50
					Trawl fisheries catch-at-age	50
2	Mar–May	None	0.25	0.50		
3	Jun–Aug	Increment age	0.33	0.00		

1. M is the proportion of natural mortality that was assumed to have occurred in that time step.
2. Age is the age fraction, used for determining length-at-age, that was assumed to occur in that time step.
3. %Z is the percentage of the total mortality in the step that was assumed to have taken place at the time each observation was made.
4. Only used in a sensitivity run.

For all models discussed below, assumed values of fixed biological parameters are given in Table 1. A Beverton-Holt stock-recruitment relationship, with steepness 0.84, was assumed (Shertzer & Conn 2012). Variability in length at age around the Schnute age-length relationship was assumed to be lognormal with a constant CV of 0.1. The maximum exploitation rate was assumed to be 0.7 for the stock. The choice of the maximum exploitation rate has the effect of determining the minimum possible virgin biomass allowed by the model, given the observed catch history. This value was set relatively high because there was little external information from which to determine it. A penalty was included to penalise any model run that prevented the observed catch history from being taken, and an examination of the model outputs showed that the maximum exploitation rate was never estimated.

Biomass estimates from the resource surveys were used as relative biomass indices, with associated CVs estimated from the survey analysis (see Table 2). The survey catchability constant (q) was assumed to be constant across all years in the survey series. Catch-at-age observations were available for each research survey and from commercial observer data for the fishery. The error distributions assumed were multinomial for the proportions-at-age and proportions-at-length data, and lognormal for all other data. In the previous assessment (Horn 2017), the process error CV applied to the Chatham Rise trawl survey biomass index was reduced from 0.2 to 0.15 after it was estimated in a mode of the joint posterior distribution (MPD) run to be 0.15. Estimates of this CV value were again close to 0.15 in MPD runs so the value of 0.15 was retained for final MPD runs and applied in all Markov chain Monte Carlo (MCMC) runs. Process error CVs for the CPUE series were estimated following Francis (2011); values of 0.2 were applied to the Chatham Rise. The multinomial observation error effective sample sizes for the at-age data were adjusted using the reweighting procedure of Francis (2011); initial and adjusted (effective) sample sizes for each of the age distributions are listed in Table 6. Ageing error was assumed to occur for the observed proportions-at-age data, by assuming a discrete normally distributed error with a CV of 0.08.

Table 6: Initial sample sizes (Ninit) and adjusted sample sizes (Nadj) for each of the fishery and trawl survey age distributions used in the Chatham Rise assessment. Nadj is the effective sample size assumed in all model final runs.

Year	Fishery west		Fishery east		Trawl survey	
	*N*init	*N*adj	*N*init	*N*adj	*N*init	*N*adj
1990					125	33
1991						
1992	392	30	92	6	187	52
1993					155	41
1994	130	10			168	46
1995	166	12	87	7	109	29
1996	167	12			100	26
1997	95	8	73	4	103	27
1998	797	61	109	7	94	25
1999	441	34			86	23
2000	449	35			157	44
2001	465	36	255	19	114	30
2002	331	26			119	32
2003	209	15			52	13
2004	224	16	208	15	81	22
2005	247	18			82	22
2006	115	9			99	26
2007			201	15	107	27
2008	277	20			83	22
2009	169	13			136	37
2010	174	13			82	22
2011	136	10			66	17
2012					64	17
2013					68	17
2014	163	13			48	12
2015			141	10		
2016	232	17			83	22
2017						
2018					73	18
2019						
2020					43	12

Year class strengths were assumed known (and equal to one) for years before 1975 and after 2017, when inadequate or no catch-at-age data were available. Otherwise, year class strengths were estimated under the assumption that the estimates from the model must average one (the 'Haist parameterisation' for year class strength multipliers; Bull et al. 2012). However, for the Chatham Rise stock, Horn & Francis (2010) had shown that it was necessary to smooth the year class estimates from 1974 to 1983 to preclude the estimation of widely fluctuating strong and weak year classes that were not supported by the available data (it was suspected that the estimated strong year classes were an artefact, the consequence of a tendency for models which assume ageing error to estimate high variability in year class strength in periods with few data). The same smoothing process was included in the Chatham Rise model presented below.

For the Chatham Rise stock, the catch history assumed in all model runs was derived as follows. Using the grooming algorithms of Dunn (2003a), landings of hake reported on TCEPR and CELR forms from 1989–90 to 2018–19 were allocated to month and fishery (based on reported date, location, and depth). Annual totals for each fishery were obtained by summing the monthly totals but, for reasons described above, using a September to August year. Thus, catch histories for model years 1990 to 2019 were produced. A full description of the catch history calculation is given by McGregor (in press). It was found that the catch histories between 1990 and 2008 matched those calculated for the previous assessment but that the proportional split of catch between east and west fisheries was different between 2009 and 2016. The newly calculated values were derived from a computer script and applied to all years, whereas values calculated previously had made use of a spreadsheet, and only applied for updated years. On the assumption the values for 2009 to 2016 may have been subject to an error (possibly use of a different longitude to split east and west fisheries) they were replaced by the newly calculated values (Table 7).

Table 7: Estimated total catch (t) and estimated catch by fishery for the model years. Landings from the most recent year (2020) are mean values over 2016–2019 for each fishery.

Fishing year	Model year	West	East	Total
1974–75	1975	80	111	191
1975–76	1976	152	336	488
1976–77	1977	74	1 214	1 288
1977–78	1978	28	6	34
1978–79	1979	103	506	609
1979–80	1980	481	269	750
1980–81	1981	914	83	997
1981–82	1982	393	203	596
1982–83	1983	154	148	302
1983–84	1984	224	120	344
1984–85	1985	232	312	544
1985–86	1986	282	80	362
1986–87	1987	387	122	509
1987–88	1988	385	189	574
1988–89	1989	386	418	804
1989–90	1990	309	689	998
1990–91	1991	409	503	912
1991–92	1992	718	1 087	1 805
1992–93	1993	656	1 996	2 652
1993–94	1994	368	2 912	3 280
1994–95	1995	597	2 903	3 500
1995–96	1996	1 353	2 483	3 836
1996–97	1997	1 475	1 820	3 295
1997–98	1998	1 424	1 124	2 548
1998–99	1999	1 169	3 339	4 508
1999–00	2000	1 155	2 130	3 285
2000–01	2001	1 208	1 700	2 908
2001–02	2002	454	1 058	1 512
2002–03	2003	497	718	1 215
2003–04	2004	687	1 983	2 670
2004–05	2005	2 585	1 434	4 019
2005–06	2006	184	255	439
2006–07	2007	270	683	953
2007–08	2008	259	901	1 160
2008–09	2009	1 084	838	1 922
2009–10	2010	275	134	409
2010–11	2011	777	165	942
2011–12	2012	108	101	209
2012–13	2013	249	117	366
2013–14	2014	109	96	205
2014–15	2015	139	83	222
2015–16	2016	249	209	458
2016–17	2017	302	124	426
2017–18	2018	228	173	401
2018–19	2019	364	93	457
2019–20	2020	286	150	436

3.1 Prior distributions and penalty functions

The assumed prior distributions used in the Chatham Rise assessment are given in Table 8. The priors for B_0 and year class strengths were intended to be relatively uninformed and had wide bounds.

The prior for the Chatham Rise survey *q* was informative and was estimated from a simulation exercise (Horn 2013b). This assumed that the catchability constant was the product of areal availability, vertical availability, and vulnerability and the simulation estimated a distribution of possible values for the catchability constant by assuming that each of these factors was independent and uniformly distributed. A prior was then determined by assuming that the resulting, sampled, distribution was lognormally distributed. Values assumed for the parameters were 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 and 0.40.

Priors for the trawl fisheries selectivity parameters were assumed to be uniform. In the previous assessment (Horn 2017), a sensitivity run was conducted where the age at full selectivity for the survey was encouraged to be at a value markedly lower than estimated in the unconstrained models. In that run, priors for the trawl survey selectivity parameters were assumed to have a normal distribution, with a tight distribution set for age at full selectivity (s1, see Table 8), but an essentially uniform distribution for parameters sL and sR. This was later adopted as the new base case parameterisation and is used in all models presented below.

Penalty functions were used to constrain the model so that any combination of parameters that resulted in a stock size that was so low that the historical catch could not have been taken was strongly penalised, and to ensure that all estimated year class strengths averaged 1. For the Chatham Rise stock they were also used to smooth the year class strengths estimated over the period 1974 to 1983.

Table 8: The priors assumed for key distributions (when estimated). The parameters are mean (in natural space) and CV for lognormal and normal priors and mean (in natural space) and standard deviation for normal-by-stdev priors.

Stock	Parameter	Distribution	Parameters		Bounds	
Chatham Rise	B_0	Uniform-log	–	–	10 000	250 000
	Survey *q*	Lognormal	0.16	0.79	0.01	0.40
	CPUE *q*	Uniform-log	–	–	1e-8	0.01
	YCS	Lognormal	1.0	1.1	0.01	100
	Selectivity (fishery)	Uniform	–	–	1	25–200*
	Selectivity (survey, s1)	Normal-by-stdev	8	1	1	25
	Selectivity (survey, sL, sR)	Normal-by-stdev	10	500	1	50–200*

* A range of maximum values was used for the upper bound.

4. MODEL ESTIMATES FOR CHATHAM RISE HAKE

4.1 Developing a 'base' model

Model parameters were estimated using Bayesian methods implemented using the CASAL v2.30 software. However, only the mode of the joint posterior distribution (MPD) was estimated in preliminary runs. For final runs, the full posterior distribution was sampled using Markov chain Monte Carlo (MCMC) methods, based on the Metropolis-Hastings algorithm. Full details of the CASAL algorithms, software, and methods were given by Bull et al. (2012).

Some initial investigations were completed to develop a 'base' model. The initial structure of the model followed previous assessments, in which sensitivity runs were completed and evaluated. The summer trawl survey series exhibited a relatively smooth trend over time and on this basis was probably a reasonable index of relative abundance (Figure 3). Consequently, in the model development stage it was assumed that any ‘good’ assessment model should fit the survey series well.

An initial model was set up as in the base case from the previous assessment (Horn 2017). The partition excluded sex and maturity and a constant value of 0.19 was used for *M*. No CPUE series was incorporated. The model used three selectivity ogives: survey selectivities for the January *Tangaroa* resource survey series, and selectivities for each of the two commercial fisheries (i.e., west, east). Selectivities were assumed constant across years in the fisheries and the survey series. All selectivity ogives were estimated using the double-normal parameterisation.

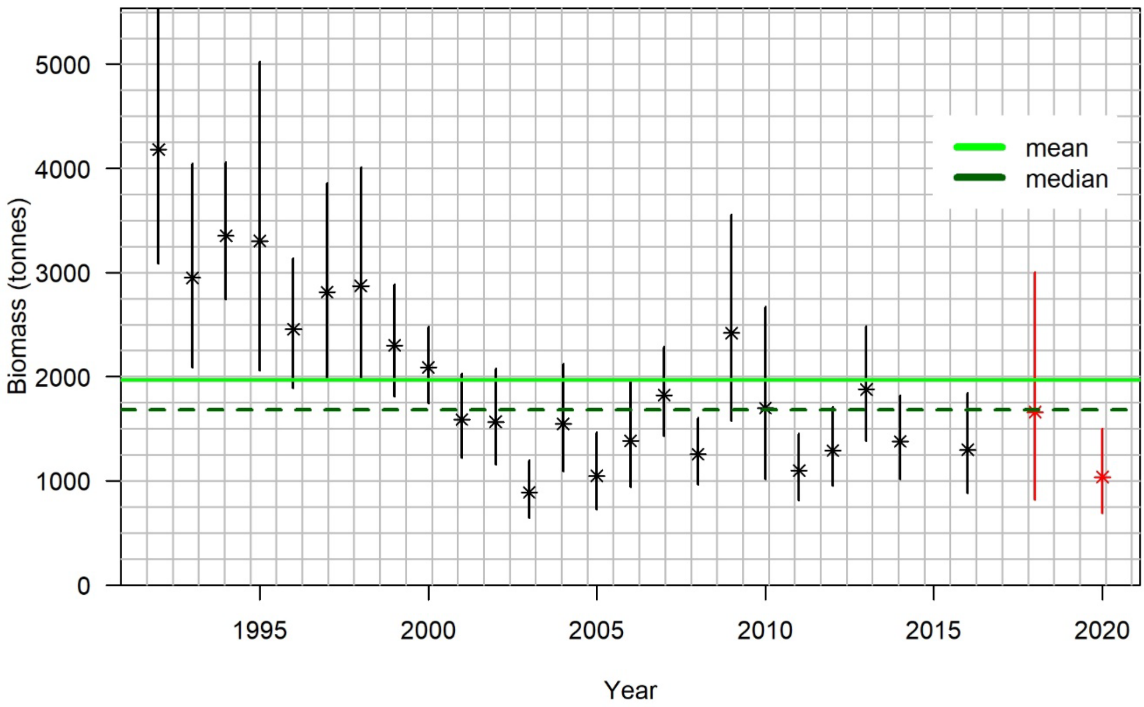

Figure 3: Trawl survey relative biomass. Vertical lines show the 95% confidence intervals. Green and dashed horizontal lines show the mean and median values over the full survey time series; red entries are new data since the previous assessment.

Initial sensitivity runs involved the addition of the CPUE index for the east fishery, CPUE index for the whole Chatham Rise (i.e., using the data of the east and west fisheries combined), and the CPUE indices for the east and west fisheries added separately. The trends in CPUE are different between the east and west fisheries. Diagnostics from MPD runs showed the fit to the west CPUE series to be poor and the fit to the trawl survey abundance series to be progressively less good moving from using CPUE for the east fishery to using CPUE for the whole Chatham Rise to using CPUE indices for both east and west fisheries (Figure 4). On the basis any ‘good’ assessment model should fit the survey series well the Deepwater Working Group (DWWG) concluded it was reasonable to use the east CPUE for a sensitivity run but rejected use of the west fishery and whole Chatham Rise CPUEs.

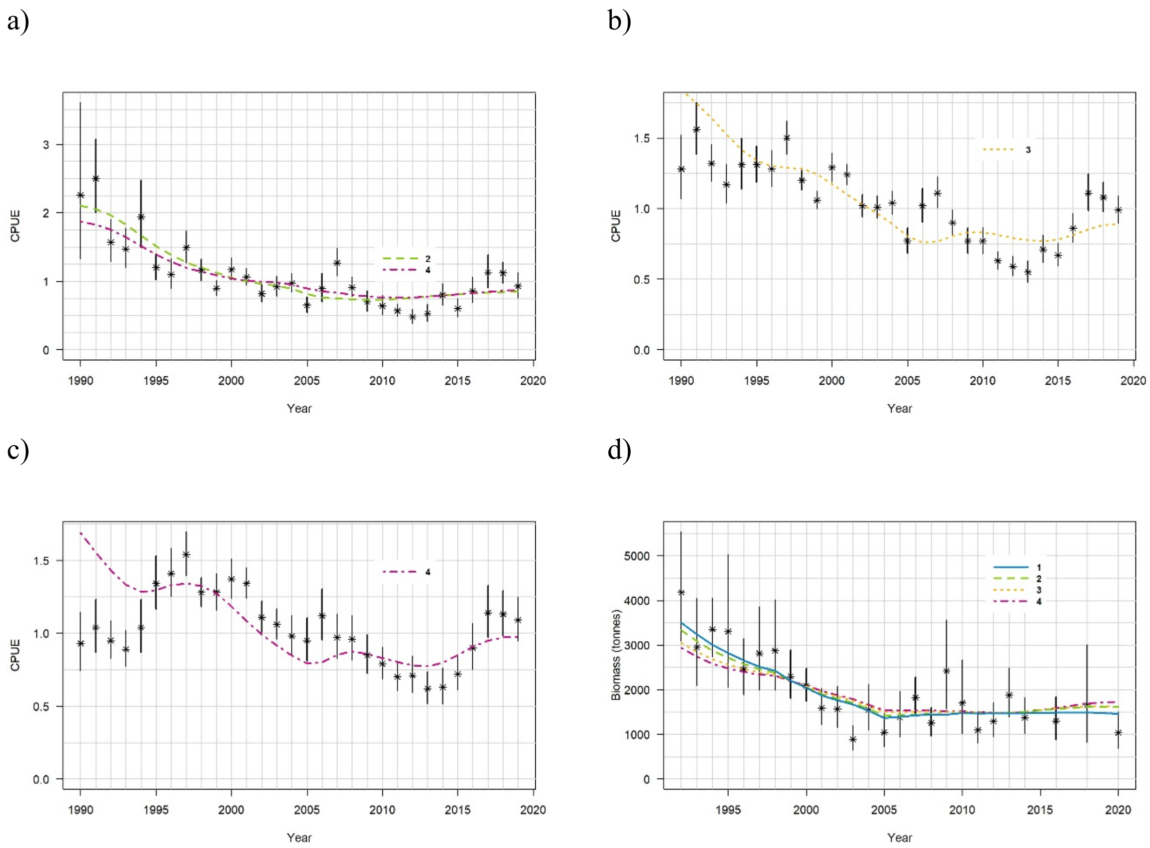

Figure 4: MPD fits to a) CPUE from east fishery; b) CPUE from fisheries covering the whole Chatham Rise; c) CPUE from the west fishery; and d) trawl survey relative biomass. Vertical lines show the 95% confidence intervals. Models are 1) initial base case (i.e., no CPUE used); 2) CPUE-east included; 3) CPUE for full Chatham Rise included; and 4) CPUE-east and CPUE-west both included as separate indices.

MPD estimates of selectivities for both fisheries and the survey reflected the chosen double normal parameterisation, but the posterior distribution for the east fishery (and to a lesser extent the trawl survey) tended towards being logistic, even when a double normal was offered. The median of the west fishery had a strongly declining right hand limb as expected (Figure 5). MPD runs were investigated with a) the east fishery selectivity parameterised as logistic and b) both the east fishery and trawl survey parameterised as logistic. Changing the selection model to logistic caused a poorer fit to the plus age group (Figure 6), but otherwise fits to data were little altered. The DWWG concluded that a model with the east fishery selectivity made logistic should become the base model on the grounds it gave a similar likelihood value to the previous base model, while being a more parsimonious model, and because it lessens the danger of 'cryptic biomass' being generated.

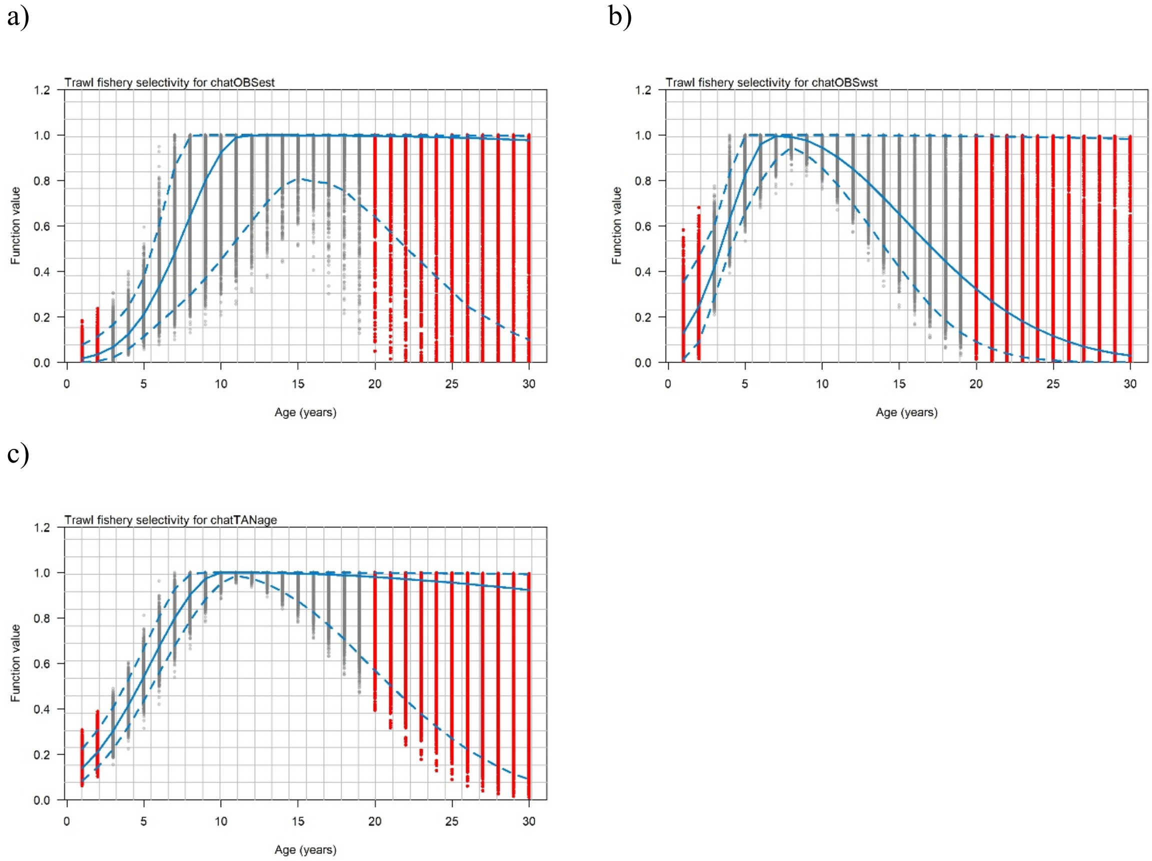

Figure 5: Selectivities for 'old base run', (i.e., run with all selectivities parameterised as double normal) for a) east trawl fishery; b) west trawl fishery; and c) trawl survey. Grey and red dots are the selectivity calculated for each age for each link of the MCMC chain over ages with supplied data and remaining ages in the model respectively, solid blue line is the median, dashed blue lines are the 95% upper and lower credible intervals.

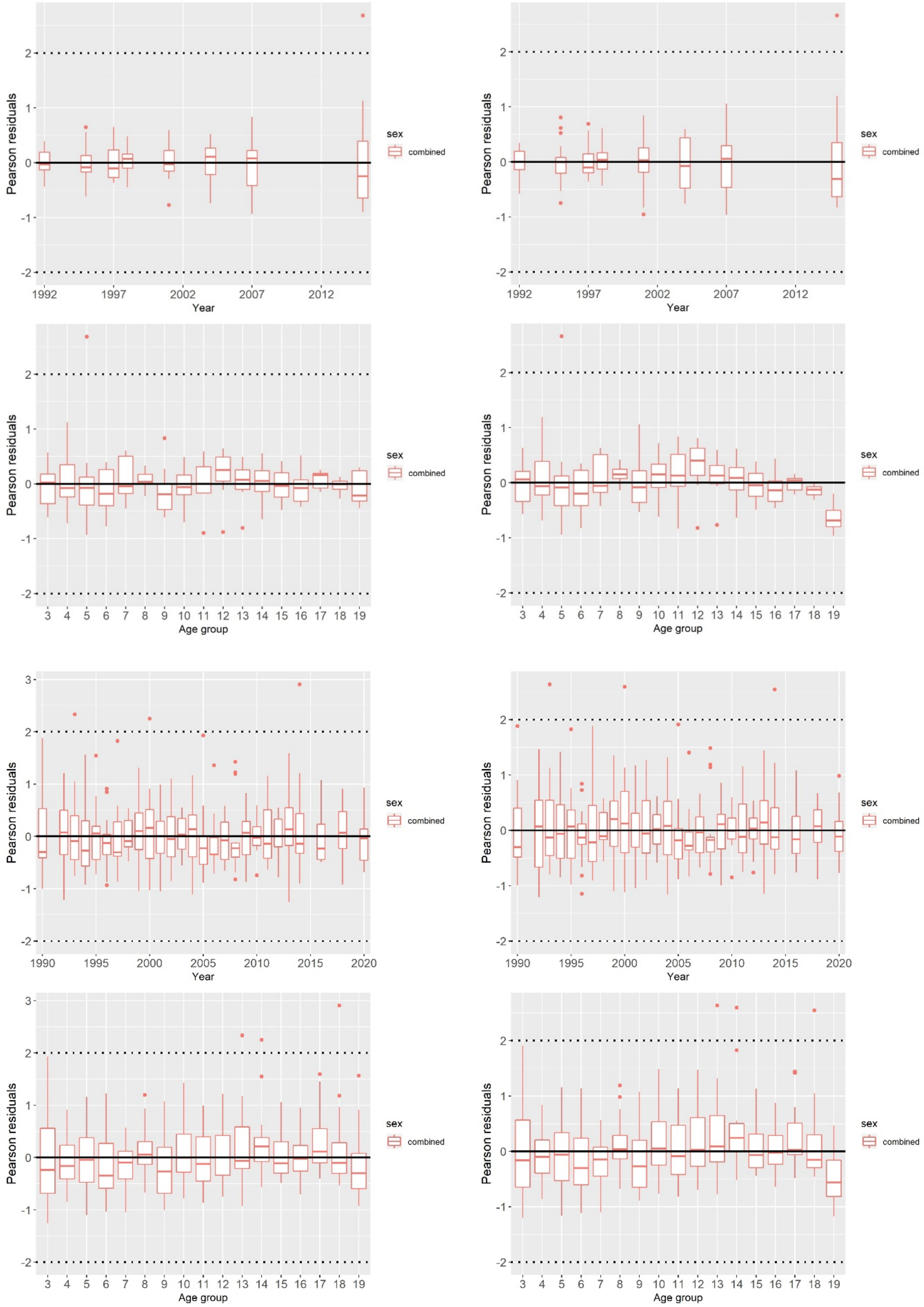

Figure 6: Pearson residuals for top row) east fishery and bottom row) *Tangaroa* survey age compositions using left) ‘old base run’, (i.e., run with all selectivities parameterised as double normal); right) selectivity parameterised as logistic.

Table 9 summarises the base and final sensitivity runs chosen, with the MPD estimates for B_0 and $B_{current}$(% B_0). The 'Base run', 'Old base run', and 'CPUE-east' runs were fully investigated (MCMC runs and projections performed). The 'High *M*' and 'Low *M*' models were run to obtain MPD estimates only.

Table 9: Key model run assumptions and MPD estimates for B_0 and $B_{current}$(% B_0).

Key run assumptions	B_0 (t)	$B_{current}$(% B_0)
1. Base run.	36 817	52
All commercial CPUE excluded; Trawl survey abundance index included Selectivity double normal for trawl survey and western fishery, logistic for eastern fishery 'Tight' normal prior on age at full selectivity in survey Single sex *M* (fixed value of 0.19) Trawl survey and fishery proportions at age combined over sexes		
2. Old base case run.	47 413	55
Same as Base run, but selectivity double normal for trawl survey and both fisheries		
3. High *M* run.	40 334	55
Same as Base run, but fixed *M* value raised from 0.19 to 0.23		
4. Low *M* run.	35 827	47
Same as Base run, but fixed *M* value lowered from 0.19 to 0.15		
5. CPUE-east run.	40 515	58
Same as Base run, but Fishery-East CPUE included		

Model fits to the age composition data (trawl survey proportion-at-age and trawl fishery proportion-at-age) were all reasonable and, for the survey and western fishery, were almost indistinguishable between model runs (see Appendix B). The exception was the east fishery age classes in 2015 where large proportions of age 4 and 5 fish were not reflected by the fits (Figure B3). Fits to the survey biomass index were also similar, with the exception that the CPUE-east model estimated a slightly higher biomass in the final years (Figure 7). This model was able to fit the CPUE-east data reasonably well (Figure 7).

The effect of changing from assuming a double normal ('Old base run') to a logistic selectivity ('Base run') for the eastern fishery was to scale the level of spawning stock biomass (*SSB*) estimated throughout the time series (Figure 8). The difference in *SSB* as a percentage of B_0 for these two models was relatively small. A bigger difference in % B_0 in the final year occurred between the base and 'CPUE-east' models, with the latter model suggesting a higher % B_0. Only the 'Low *M*' model estimated *SSB* to have fallen to the 40% B_0 threshold at any point in the time series (Figure 8).

It had been shown previously (Horn & Francis 2010) that year class strength estimates were poorly estimated for years where only older fish were available to determine age class strength (i.e., before 1984). Consequently, these year class strength estimates were smoothed, and all models investigated estimated a period of generally higher than average recruitment (Figure 9). Since then recruitment appears to be cyclic, with a large recruitment occurring roughly once every ten years (Figure 9).

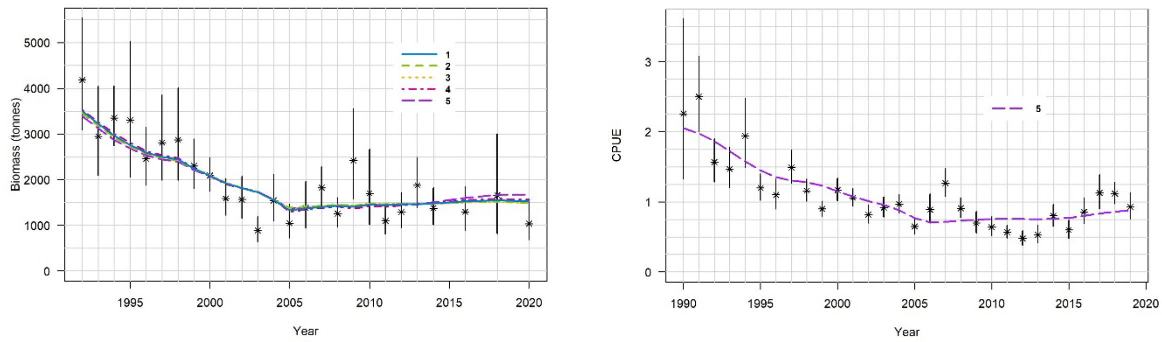

Figure 7: Model MPD fits to biomass indices for the trawl survey (left) and CPUE-east fishery (right). (1) Base run, (2) Old base run, (3) High *M* run, (4) Low *M* run, (5) CPUE-east run. Vertical lines show the 95% confidence intervals.

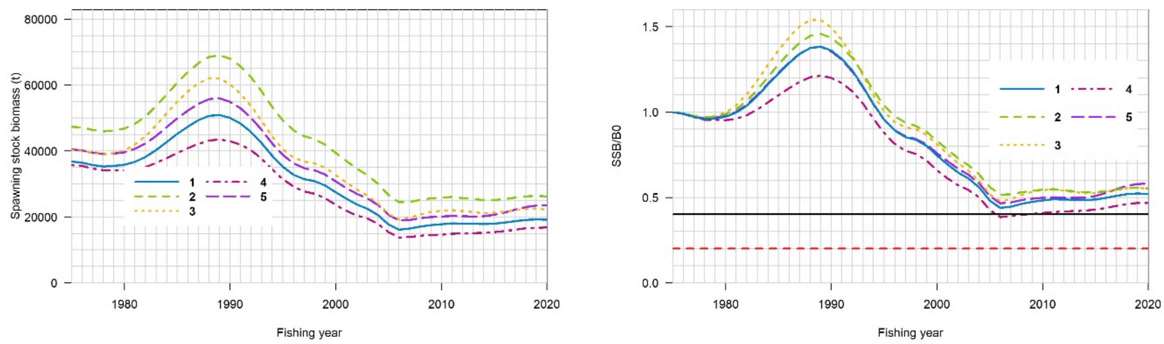

Figure 8: MPD estimates of *SSB* (left) *SSB*/B_0 (right). (1) Base run, (2) Old base run, (3) High *M* run, (4) Low *M* run, (5) CPUE-east run. Black solid horizontal and red dashed horizontal lines in right hand figure show the 40% B_0 and 20% B_0 thresholds respectively.

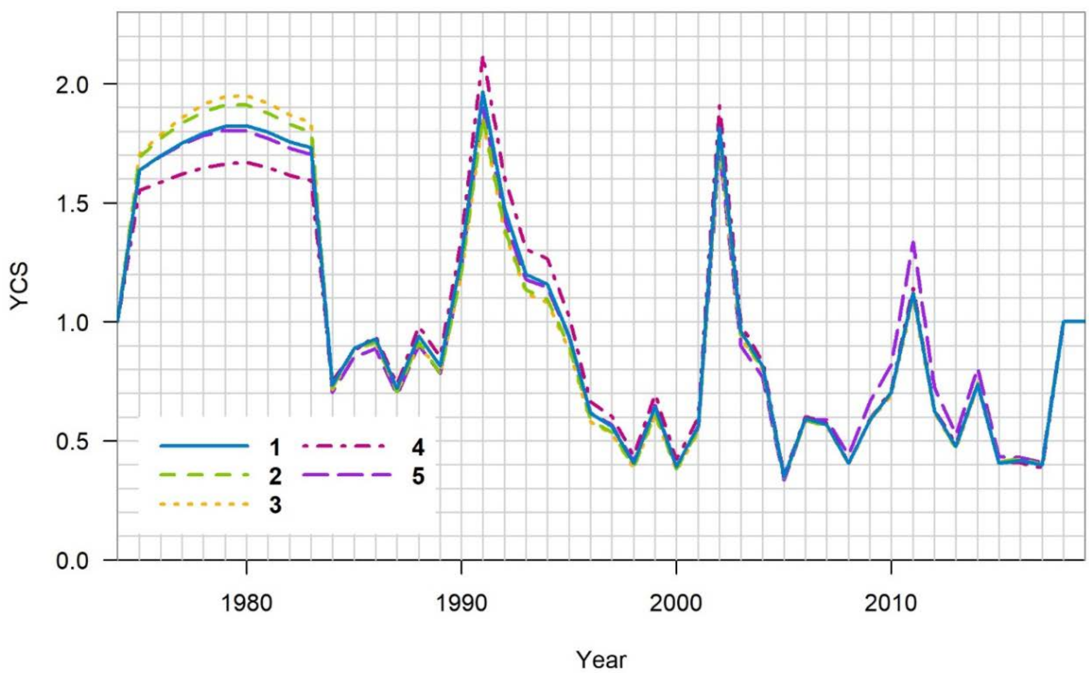

Figure 9: MPD year class strength (YCS) estimates for model runs (1) Base run, (2) Old base run, (3) High *M* run, (4) Low *M* run, (5) CPUE-east run.

4.2 Model estimation using MCMC

For base case and sensitivity runs chosen to be fully investigated the full posterior distribution was sampled using MCMC methods, based on the Metropolis-Hastings algorithm. Initially MCMCs were estimated using 8×10^6 iterations, a burn-in length of 3×10^6 iterations, and with every 5000th sample kept from the final 5×10^6 iterations (i.e., a final sample of length 1000 was taken from the Bayesian posterior).

Results showed MCMC distributions for B_0 well to the left of the MPD result, but the MPD result for current stock status was approximately in the middle of MCMC distribution. Cross checks confirmed the MPD results were at a true minimum and parameters to be away from boundary values. However, with the model using double normal selectivity for both fisheries, selectivity parameters for the eastern fishery were found to be highly correlated and trace plots of individual parameters found a 'flip-flopping' of the sR parameter (which controls the rate of decrease in selectivity from the maximum at higher ages) for both the eastern fishery and survey selectivity (Figure 10) indicating the MCMC was not properly converged. The parameter covariance matrix calculated at the end of the initial MCMC run was supplied to CASAL and the MCMC run re-started. This allowed for the runs to converge without requiring a very large increase in iterations.

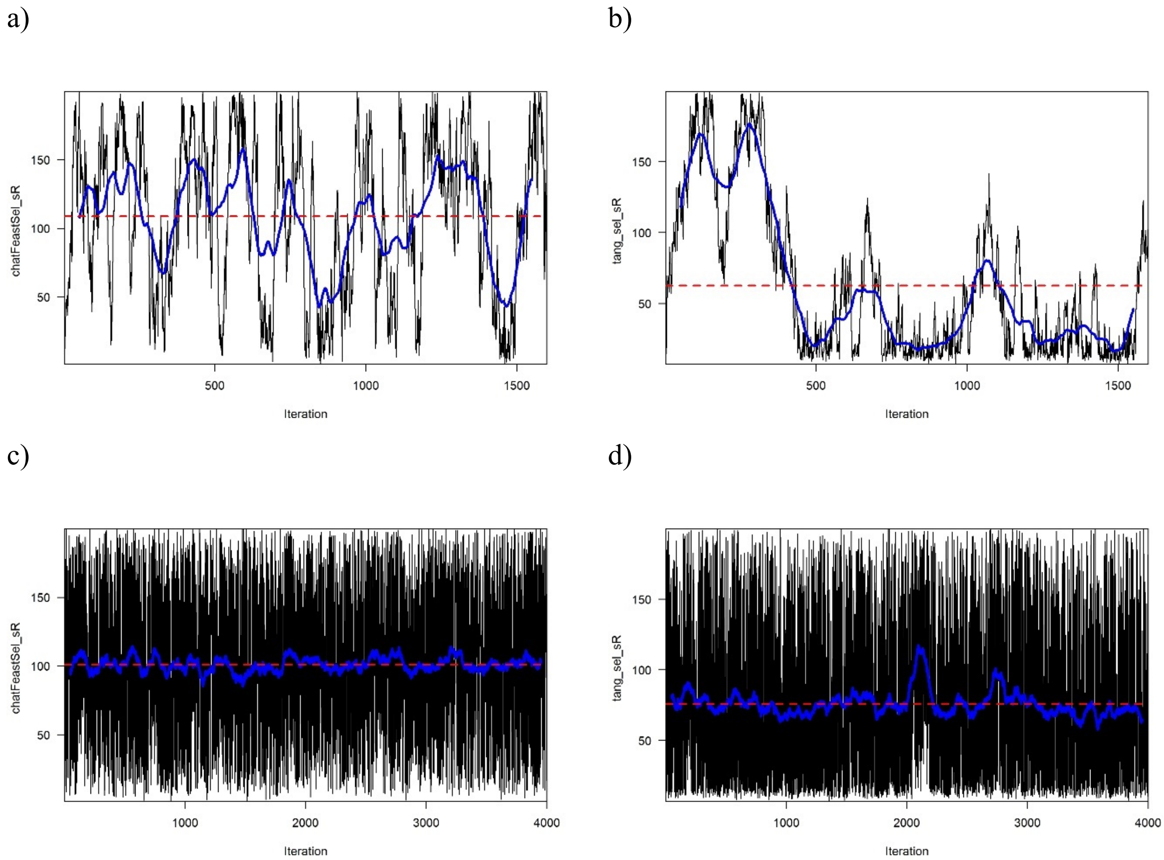

Figure 10: Trace diagnostic plots of the MCMC chain for sR selectivity parameter in the old base model run for a) eastern fishery during initial chain of 8x106 iterations; b) survey during initial chain of 8x106 iterations; c) eastern fishery when MCMC is re-started using covariance matrix calculated from the initial MCMC run; d) survey when MCMC is re-started using covariance matrix calculated from the initial MCMC run. The red dashed line is the mean of the entire chain, the blue line is the moving mean of 100 points of the chain.

MCMC runs were carried out for the model runs 'Base', 'Old base', and 'CPUE-east'. Every 5000th sample was kept after re-starting the MCMC run as described above and sample lengths taken for the Bayesian posterior were 1000, 4000, and 3200, respectively, dependent on visual inspection of trace plots and cumulative frequencies after 8x10^6 iterations had been performed. The estimates for B_0, $B_{current}$, and $B_{current}$(% B_0) were very similar between the base case and old base case models. Values for all three parameters were higher from the CPUE-east run, but there was a large overlap in credible intervals between all three models (Table 10).

Table 10: Bayesian median (t) and 95% credible intervals of B_0, $B_{current}$, and $B_{current}$ as a percentage of B_0 for the Chatham Rise model runs.

Model run	B_0	$B_{current}$	$B_{current}$ (% B_0)
Base case	32 838 (28 280–42 721)	18 150 (13 204–27 258)	55.1 (45.7–65.9)
Old base case	32 859 (27 998–43 444)	18 237 (13 175–27 659)	55.4 (45.4–66.8)
CPUE-east	34 367 (29 504–44 113)	20 035 (15 096–28 979)	58.0 (49.6–68.1)

The similarity of results between the base case and old base case contrasts to differences found between the MPD results, especially for B_0 (see Figure 8). This was because the MPD result for the old base case was to quite an extreme high value of the posterior distribution for B_0 for the old base case and less so for the new base case (Figure 11). The occurrence of the MPD result in the upper tail of the posterior distribution was found in the previous assessment (Horn 2017) and is believed to occur when the MCMC posterior distribution is asymmetric such that the point where the objective function is at its absolute minimum (i.e., the MPD point estimate) is not in the area of greatest density of the posterior distribution.

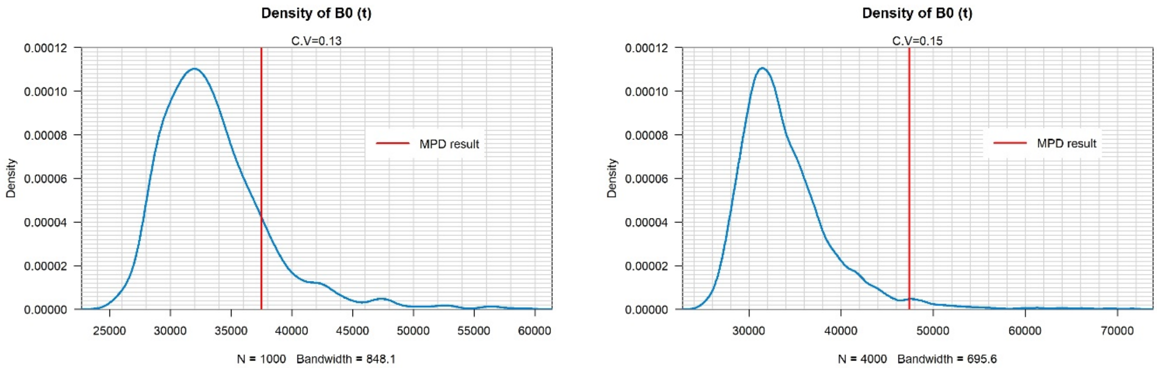

Figure 11: Estimated posterior distribution for B_0 in left) base case run and right) 'Old-base case' run (all selectivities set to double normal).

As noted above, selectivities for the east fishery tended towards a logistic distribution when a double normal distribution was offered (Figure 12). Credible intervals were much tighter at older ages when a logistic distribution was used. All models estimated 50% selectivity for the east fishery by about age 7. Full selectivity for the east fishery was estimated at a younger age (age 11) from the old base model compared with the models with logistic parameterisation (age 15).

The median posterior selectivity from all three models were very similar for the west fishery (Figure 13), but the upper credibility bound for the CPUE-east model gave slightly greater confidence to the selectivity results at older ages. All models estimated 50% selectivity for the west fishery by about age 3 or 4 and full selectivity at age 7. The median posterior selectivities from all three models were again very similar for the trawl survey (Figure 14). The declines in selectivity at older ages were very small, though the credibility intervals became very wide at older ages. All models estimated 50% selectivity for the trawl survey by about age 4 or 5 and full selectivity at age 10. This was consistent with the informed prior on survey full selectivity which strongly encouraged this parameter to be 8 ± 2 years (see Table 8).

The estimated posterior distribution of the Chatham Rise resource survey catchability constant *q* was very similar from all three models with median values of 0.085 (‘CPUE-east’ run) to 0.1 (Base run) (Figure 15). The new base case value was similar to the base case from the previous assessment (median of 0.11, Horn 2017).

The exploitation rate (catch over vulnerable biomass) from the base case is shown in Figure 16. For most years between 1993 and 2005 the rate was higher than that estimated to give 40% B_0 at equilibrium. For all years since 2012, however, the exploitation rate has been very low.

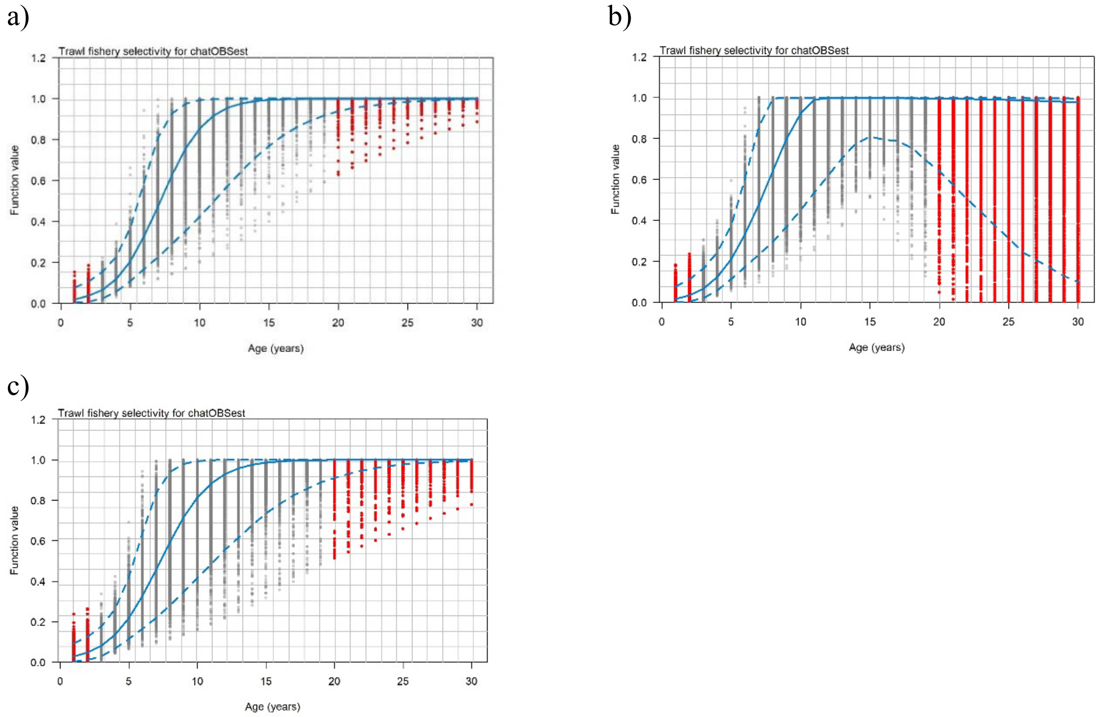

Figure 12: Selectivities for the east fishery from a) Base run, b) ‘Old base’ run (all selectivities double normal), and c) ‘CPUE-east’ run. Grey and red dots are the selectivity calculated for each age for each link of the MCMC chain over ages with supplied data and remaining ages in the model, respectively; solid blue line is the median; dashed blue lines are the 95% upper and lower credible intervals.

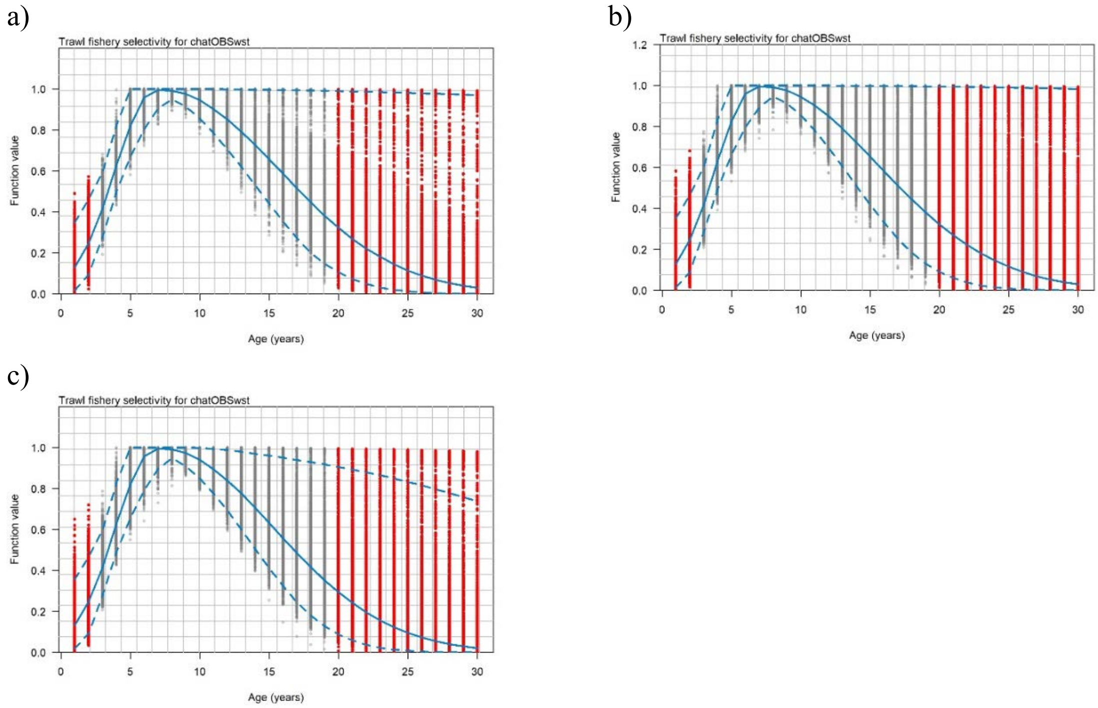

Figure 13: Selectivities for the west fishery from a) Base run, b) 'Old base' run (all selectivities double normal), and c) 'CPUE-east' run. Grey and red dots are the selectivity calculated for each age for each link of the MCMC chain over ages with supplied data and remaining ages in the model, respectively; solid blue line is the median; dashed blue lines are the 95% upper and lower credible intervals.

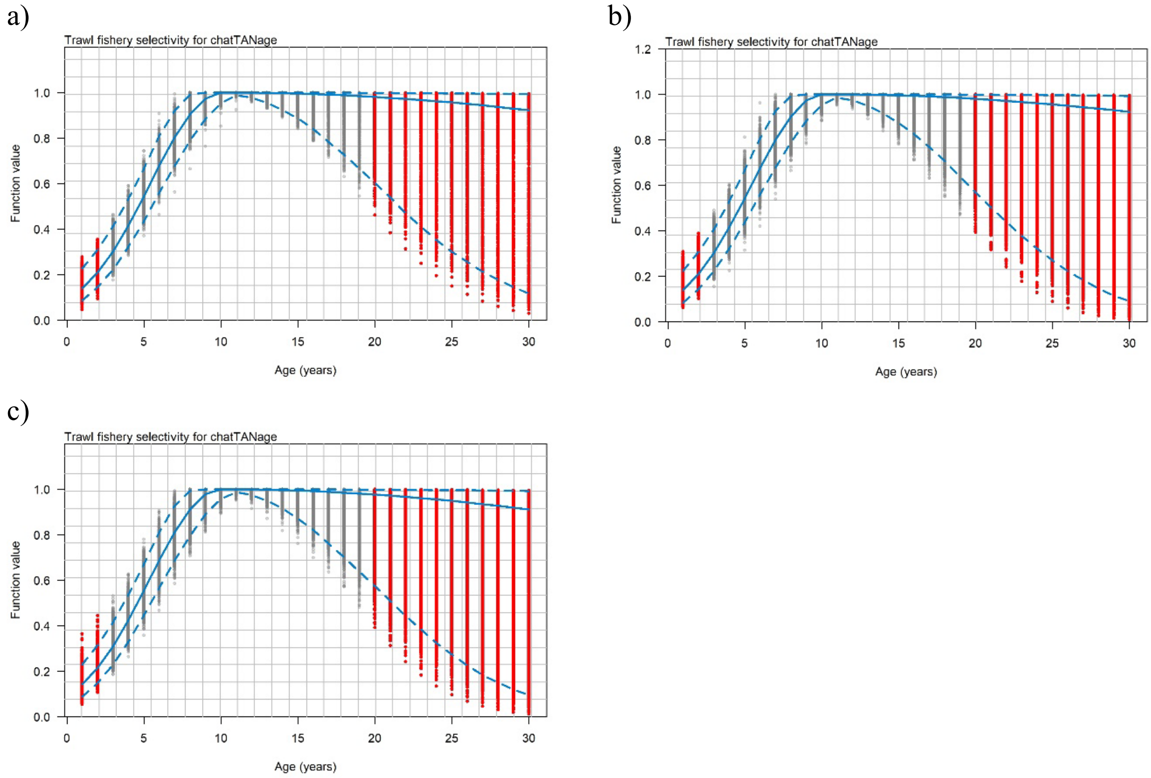

Figure 14: Selectivities for the trawl survey from a) Base run, b) 'Old base' run (all selectivities double normal), and c) 'CPUE-east' run. Grey and red dots are the selectivity calculated for each age for each link of the MCMC chain over ages with supplied data and remaining ages in the model, respectively; solid blue line is the median; dashed blue lines are the 95% upper and lower credible intervals.

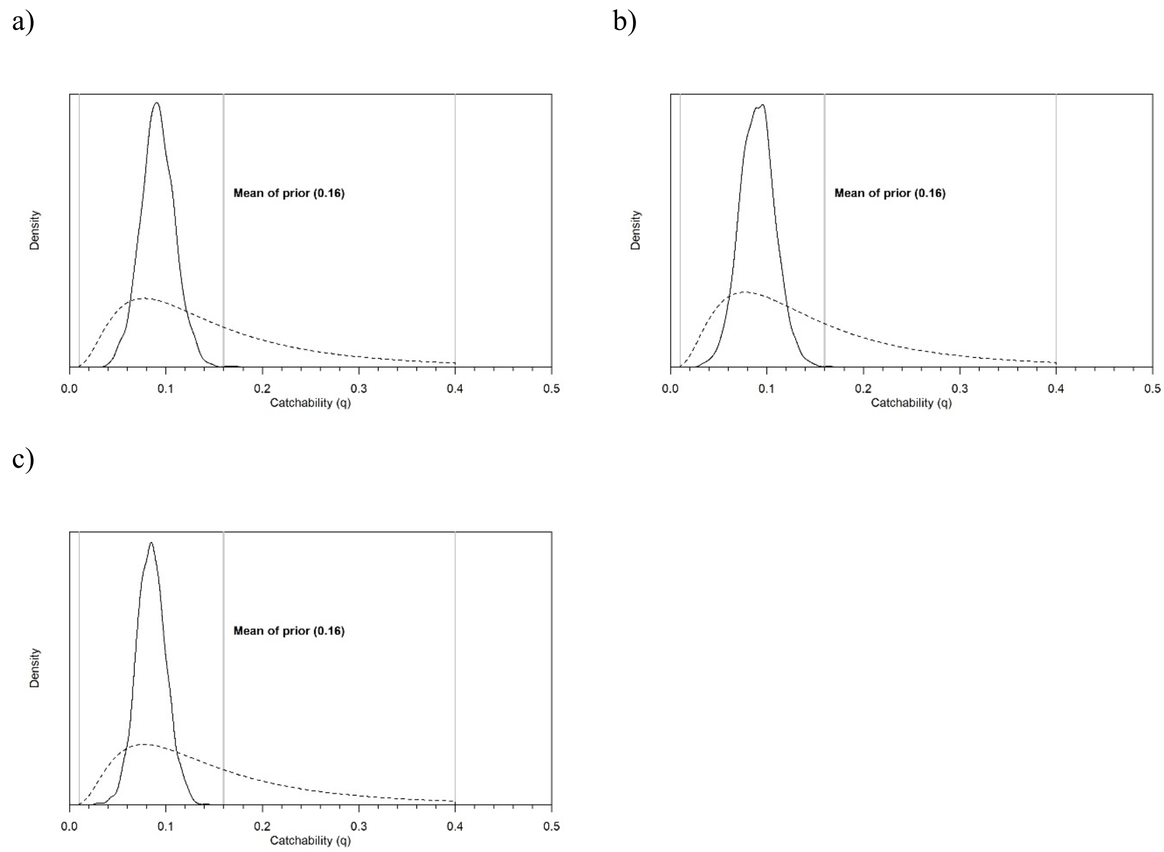

Figure 15: Estimated posterior distribution (solid line) and prior (dashed line) of the survey catchability constant *q* for the Chatham Rise resource survey for a) Base run, b) 'Old base' run (all selectivities double normal), and c) 'CPUE-east' run.

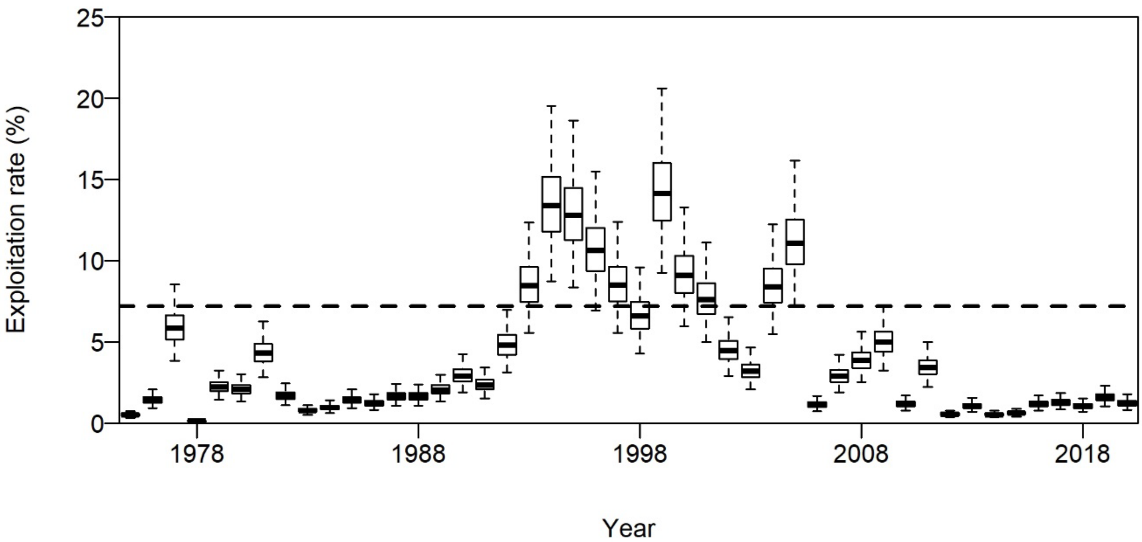

Figure 16: Exploitation rate (catch over vulnerable biomass) from the Base run. The rate is a catch weighted average of the east and west fishery exploitation rates. Boxes cover the interquartile range with horizontal line at the median and whiskers denote 95% confidence intervals. Horizontal dashed line gives the exploitation rate predicted to give a biomass of 40% B_0 at equilibrium.

4.3 Biomass projections

Biomass projections were made under two assumed future catch scenarios (Table 11). The first used the average catches from the last six years for the east and west fisheries. The second assumed that the TACC is taken, with the proportional split between east and west fisheries matching that found from the last six years of catch data. Two alternative approaches to estimating future year class strengths were also employed. The first made use of all estimated YCS; the second based future year class strengths on the most recent 10 estimated YCS only.

Table 11: Future catch options used in the projections. Relative year class strengths (YCS) from 2021 onwards were selected in two ways: (1) the randomised YCS were resampled using all estimated YCS; (2) the randomised YCS were resampled using the most recent 10 estimated YCS.

	Total catch (t)	East fishery catch (t)	West fishery catch (t)
Average last 6 years	362	130	232
TACC (split as for av. catches)	1 800	648	1 152

Projections were carried out for the Base run, Old base run, and CPUE-east run. In all models taken to projection, highest values of B_{2025} were predicted when combining YCS selected from all past estimated YCS and catch made equal to recent catch and lowest values of B_{2025} were predicted when combining YCS selected from those estimated for the most recent 10 years and catch based on the HAK 4 TACC. Changing between future catch assumptions made a bigger difference to future biomass predictions than changes in YCS selection criteria or changes between model variant (Table 12). Only one projection resulted in the median *SSB* falling below 40% B_0 by 2025 (base model using recent YCS and TACC future catch). Plots of all projections using the base model are in Figure 17–Figure 20 and plots for the other models are shown in Appendix C.

Table 12: Projections from MCMC runs 'Base', 'Old base', and 'CPUE-east'. Median and 95% upper and lower quartiles for B_{2025}, B_{2025}(% B_0), and B_{2025}(% B_{2020}) under four future catch options.

	Future catch	Future YCS	B_{2025} (t)	B_{2025}(% B_0)	B_{2025}(% B_{2020})
Base Run	362 t (Average last 6 years)	All estimated YCS	19 600 (13 000, 32 400)	59 (44, 80)	108 (85, 137)
	362 t (Average last 6 years)	Last 10 yrs YCS	17 800 (11 500, 32 000)	54 (39, 78)	98 (77, 135)
	1800 t (HAK 4 TACC, split as for av. catches)	All estimated YCS	15 000 (8 400, 27 500)	45 (29, 67)	82 (58, 112)
	1800 t (HAK 4 TACC, split as for av. catches)	Last 10 yrs YCS	13 000 (6 900, 27 000)	40 (23, 66)	72 (48, 112)
Old base Run	362 t (Average last 6 years)	All estimated YCS	19 800 (12 900, 33 600)	60 (44, 79)	108 (86, 138)
	362 t (Average last 6 years)	Last 10 yrs YCS	18 000 (11 100, 32 200)	54 (39, 76)	98 (78, 132)
	1800 t (HAK 4 TACC, split as for av. catches)	All estimated YCS	15 100 (8 400, 29 000)	46 (29, 67)	82 (59, 111)
	1800 t (HAK 4 TACC, split as for av. catches)	Last 10 yrs YCS	13 300 (6 400, 27 500)	40 (23, 64)	72 (48, 106)
CPUE-east Run	362 t (Average last 6 years)	All estimated YCS	21 500 (14 200, 35 400)	63 (47, 82)	107 (87, 137)
	362 t (Average last 6 years)	Last 10 yrs YCS	20 000 (12 700, 34 400)	58 (42, 81)	100 (79, 131)
	1800 t (HAK 4 TACC, split as for av. catches)	All estimated YCS	16 800 (9 600, 30 600)	49 (32, 70)	84 (61, 114)
	1800 t (HAK 4 TACC, split as for av. catches)	Last 10 yrs YCS	15 200 (8 100, 29 600)	44 (27, 68)	76 (53, 109)

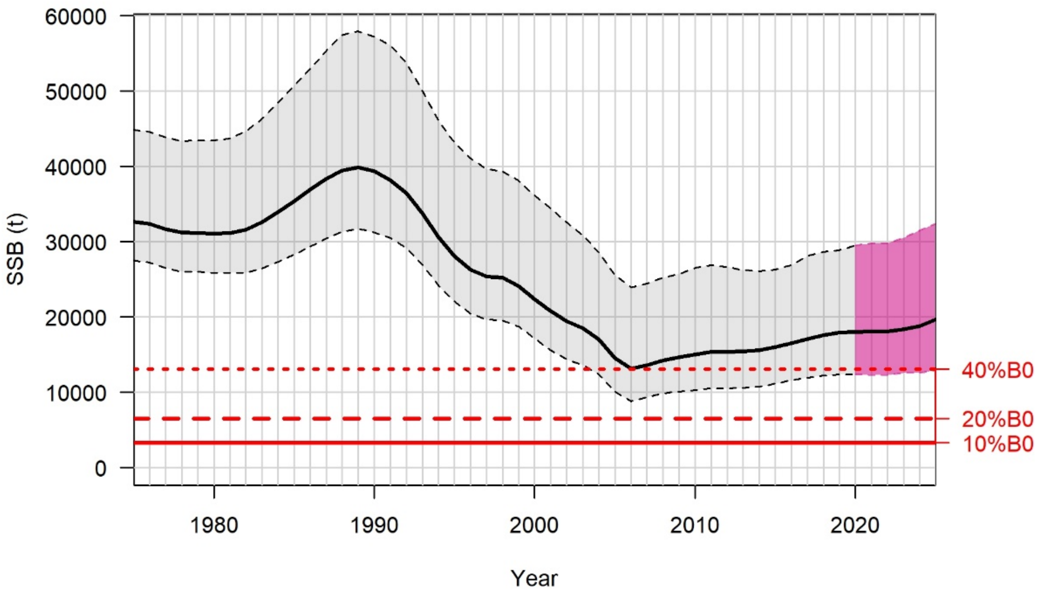

Figure 17: Projection using MCMC. Base run using all estimated year class strengths to estimate future year class strengths. Future catch option: Average last 6 years.

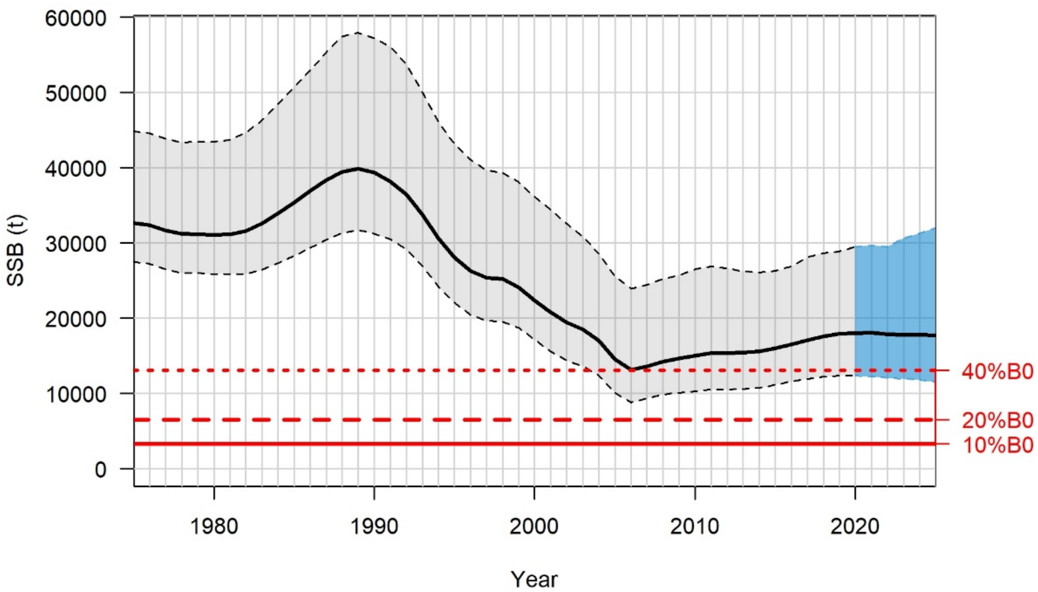

Figure 18: Projection using MCMC. Base run using most recent 10 estimated year class strengths to estimate future year class strengths. Future catch option: Average last 6 years.

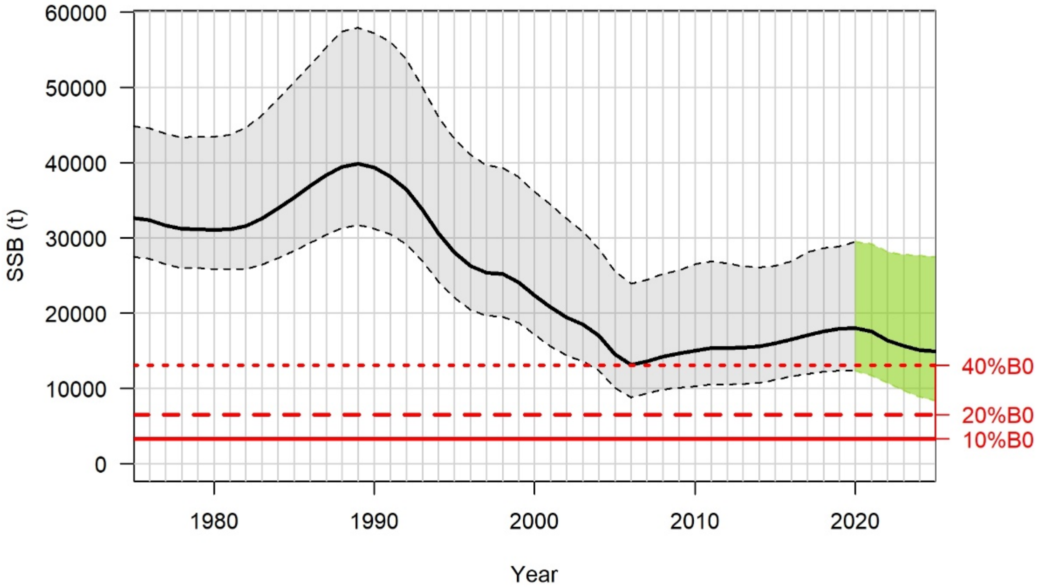

Figure 19: Projection using MCMC. Base run using all estimated year class strengths to estimate future year class strengths. Future catch option: TACC.

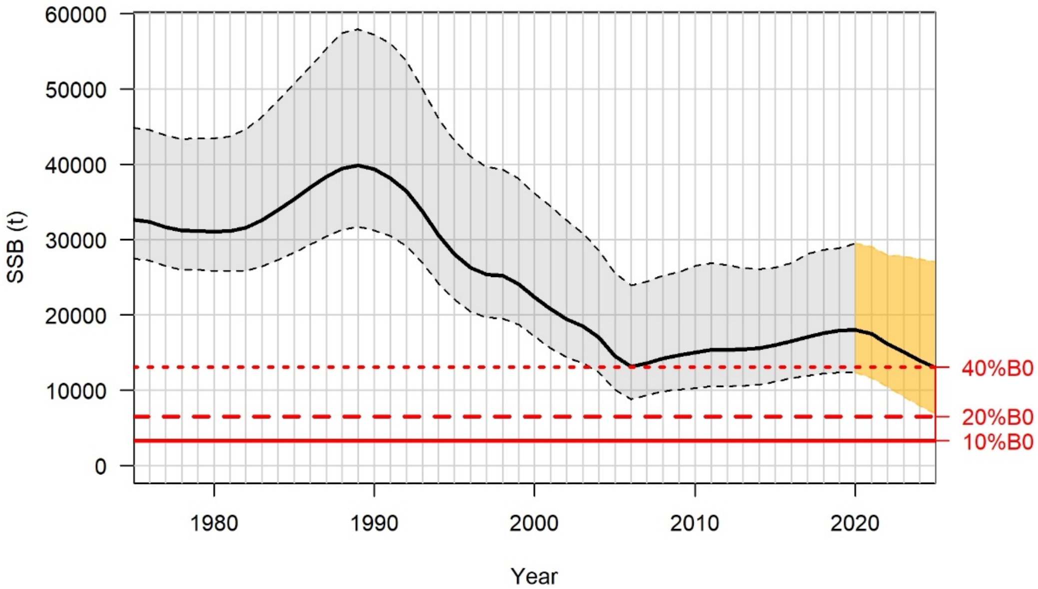

Figure 20: Projection using MCMC. Base run using most recent 10 estimated year class strengths to estimate future year class strengths. Future catch option: TACC.

4.4 Management biomass targets

Probabilities that current and projected biomass will be above the target reference point of 40% B_0 or drop below selected management reference points (i.e., soft limit, 20% B_0; hard limit, 10% B_0) are shown, for the Base model run in Table 13. It appears very unlikely (i.e., less than 1%) that B_{2025} will be lower than the soft target of 20% B_0, but at the higher catch level there is an approximate 28% to 52% probability that the stock will fall below the target level (40% B_0) depending on assumption about future recruitment strength.

Table 13: Probabilities that $B_{current}$ (2020) and projected (B_{2025}) biomass will be greater than 40% and less than 20% or 10% of B_0. Projected biomass probabilities are presented for four scenarios of future annual catch.

'Current' year	Future catch	Future YCS	P($B_{current}$>40% B_0)	P($B_{current}$<20% B_0)	P($B_{current}$<10% B_0)
2020	–		0.999	0.0	0.0
2025	TACC (split as for av. catches)	All estimated YCS	0.717	0.001	0.0
2025	TACC (split as for av. catches)	Last 10 yrs YCS	0.484	0.007	0.0
2025	Average last 6 years	All estimated YCS	0.997	0.0	0.0
2025	Average last 6 years	Last 10 yrs YCS	0.969	0.0	0.0

5. DISCUSSION

HAK 4 stock status in 2019–20 from the base model was estimated to be 55% of B_0, within bounds of 46 to 66%. This is comparable with an estimate of 48% of B_0 from the previous assessment (Horn 2017) and is consistent with the projection from that assessment which predicted an increase in biomass if catches remained at the then current level. Catches have remained at that general level for several years and, if they continue to do so, the model estimated that they are likely to be sustainable (assuming no exceptional decline in future recruitments) but higher catches equal to the HAK 4 TACC are likely to cause a decline. Note that the stock assessment was for HAK 4 plus part of HAK 1, such that the HAK 4 TACC is less than the legal catch that could be taken from this stock.

Biomass estimates from the Chatham Rise research trawl series strongly suggested a steady decline in biomass from the start of the series to the mid-2000s, with biomass in 2005 at about one-third of the level in the early 1990s, with the stock estimated to be at about 40% B_0. Estimates of year class strengths indicated lower than average spawning success in recent years, except for 2002 and 2011. However, if assumed stock structure is correct and catchability unchanged, then these strong year classes have produced an upturn in the survey estimates of biomass. All model runs produced almost identical patterns of year class strengths. The YCS and survey mean age data suggest recruitment of hake may be cyclic (with an approximate 10-year cycle). If so the decadal means of recruitment suggest a decline in recruitment over time for this stock (Figure 21). Alternatively, the model has over-estimated B_0, and to explain a failure of the stock to rebuild strongly under relatively low catch (recent catch being about one tenth of that in the 1990s), the model has estimated successively lower YCS.

In the previous assessment (Horn 2017) it was noted the selectivity ogive for the eastern fishery was essentially logistic in all model runs, even though it was estimated using the double-normal parameterisation. The base model for this assessment changed the selectivity ogive for the eastern fishery to a logistic parameterisation. For all models, if a double normal parameterisation was chosen for any of the selectivities, diagnostics from the MCMC runs showed a 'flip flopping' of the estimated double normal parameter controlling the degree to which selectivity is double normal or logistic in nature. This suggests parameter space representing both logistic and double normal selectivity that give likelihoods within a tolerance of the MPD value allowing them to be included in the MCMC calculations. It may be worth investigating if, in future, a model with fewer modelled age classes helps to reduce model uncertainty with respect to selectivity. The age selected for the plus group was chosen based upon the age sampling data (age 19+). The model assumed ages up to 30+. It would be prudent to align the plus group from the model with the plus group of the data in future assessments.

The estimated survey catchability constant *q* from all models was low, suggesting the absolute catchability of the survey series was low. Work by Harley & Myers (2001), that includes data from the Chatham Rise, suggests a higher value. The prior on survey catchability could be revisited if new information on the credible ranges for the parameters used to form the prior become available.

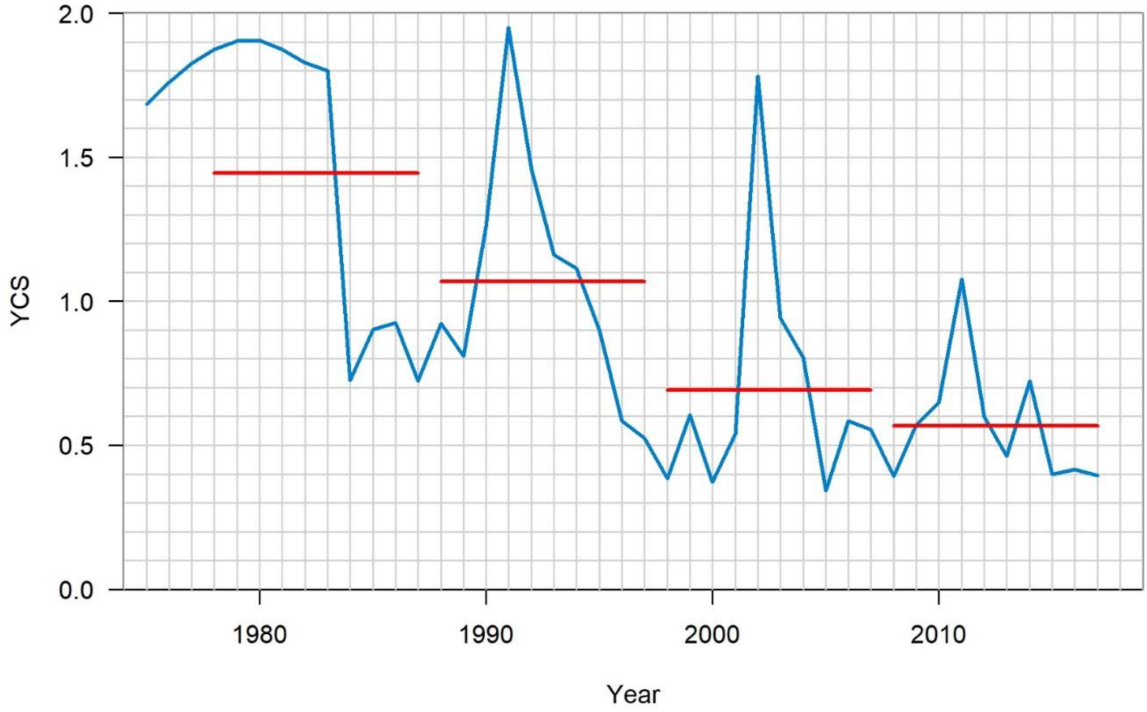

Figure 21: MPD year class strength (YCS) estimates for base model run with red horizontal lines indicating ten-year means.

The structural assumptions of the model reported here are likely to lead to the Bayesian posteriors of stock status underestimating the true level of uncertainty. Although the assessment assumed a single, combined sex, there are clear differences in the biological parameters between males and females. It is likely that the next stock assessment of hake will use the Casal2 package rather than CASAL. Because of the greater flexibility offered by Casal2, it may be prudent to revisit some of the assumptions of the current assessment, such as combined sexes and time-invariant parameters. The projected stock status relied on adequate estimation of recent year class strengths and recruitment. The sample sizes of age data from the resource survey were generally small, and the commercial catch proportions-at-age distributions have been sporadic (particularly for the eastern fishery) and based on relatively small samples. No new observer-based age data have been available since 2016. Consequently, the projections of future stock status are likely to underestimate the true level of uncertainty. It is particularly unfortunate that what was formerly the most productive fishery centred on Statistical Area 404 is now seldom fished and is generally poorly sampled.

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7. REFERENCES

Anderson, O.F.; Bagley, N.W.; Hurst, R.J.; Francis, M.P.; Clark, M.R.; McMillan, P.J. (1998). Atlas of New Zealand fish and squid distributions from research bottom trawls. *NIWA Technical Report 42*. 303 p.

Bagley, N.W.; Hurst, R.J. (1998). Trawl survey of hoki and middle depth species on the Chatham Rise January 1998 (TAN9801). *NIWA Technical Report 44*. 54 p.

Bagley, N.W.; Livingston, M.E. (2000). Trawl survey of hoki and middle depth species on the Chatham Rise January 1999 (TAN9901). *NIWA Technical Report 81*. 52 p.

Ballara, S.L. (2013). Descriptive analysis of the fishery for hake (*Merluccius australis*) in HAK 1, 4 and 7 from 1989–90 to 2010–11, and a catch-per-unit-effort (CPUE) analysis for Chatham Rise and WCSI hake. *New Zealand Fisheries Assessment Report 2013/45*. 82 p.

Ballara, S.L. (2015). Descriptive analysis of the fishery for hake (*Merluccius australis*) in HAK 1, 4 and 7 from 1989–90 to 2012–13, and a catch-per-unit-effort (CPUE) analysis for Sub-Antarctic hake. *New Zealand Fisheries Assessment Report 2015/12*. 47 p.

Ballara, S.L. (2017). 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. (2018). Descriptive analysis of the fishery for hake (*Merluccius australis*) in HAK 1, 4 and 7 from 1989–90 to 2016–17, and a catch-per-unit-effort (CPUE) analysis for Sub-Antarctic hake. *New Zealand Fisheries Assessment Report 2018/60*. 59 p.

Bull, B.; Bagley, N.W. (1999). The effects of the 1995–96 Chatham Rise survey design on abundance estimates for hake age groups. New Zealand Fisheries Assessment Research Document 99/36. 26 p. (Unpublished report held by NIWA library, Wellington.)

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

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

Colman, J.A. (1998). Spawning areas and size and age at maturity of hake (*Merluccius australis*) in the New Zealand Exclusive Economic Zone. New Zealand Fisheries Assessment Research Document 98/2. 17 p. (Unpublished report held by NIWA library, Wellington.)

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. 29 p. (Unpublished report held by NIWA library, Wellington.)

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. 23 p. (Unpublished report held by NIWA library, Wellington.)

Devine, J. (2009). Descriptive anlaysis of the commercial catch and effort data for New Zealand hake (*Merluccius australis*) for the 1989–90 to 2005–06 fishing years**.** *New Zealand Fisheries Assessment Report 2009/21*. 74 p.

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

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). 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. (2003b). Stock assessment of hake (*Merluccius australis)* for the 2002–03 fishing year. *New Zealand Fisheries Assessment Report 2003/38*. 57 p.
Dunn, A. (2004a). Stock assessment of hake (*Merluccius australis*) for the 2003–04 fishing year. *New Zealand Fisheries Assessment Report 2004/34*. 62 p.
Dunn, A. (2004b). Investigation of a minimum biomass model for the assessment of hake (*Merluccius australis*) on the west coast South Island (HAK 7). Final Research Report for Ministry of Fisheries Project HAK2003-01, Objective 5. 27 p. (Unpublished report held by Fisheries New Zealand, Wellington.)
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, Objective 4. 47 p. (Unpublished report held by Fisheries New Zealand, Wellington.)
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, M.R. (2019). Stock assessment of Sub-Antarctic hake (part of HAK 1) for 2018. *New Zealand Fisheries Assessment Report 2019/52*. 33 p.
Dunn, M.R.; Connell, A.; Forman, J.; Stevens, D.W.; Horn, P.L. (2010). Diet of two large sympatric teleosts, the ling (*Genypterus blacodes*) and hake (*Merluccius australis*). *PLOS ONE 5(10)*: e13647. doi:10.1371/journal.pone.0013647
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 (2020). Fisheries Assessment Plenary, May 2020: stock assessments and stock status. Compiled by the Fisheries Science and Information Group, Fisheries New Zealand, Wellington, 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.
Harley, S.J.; Myers, R.A. (2001) Hierarchical Bayesian models of length-specific catchability of research trawl surveys. *Canadian Journal of Fisheries and Aquatic Sciences 58*: 1569–1584.
Hoenig, J.M. (1983). Empirical use of longevity data to estimate mortality rates. *Fisheries Bulletin 81*: 899–903.
Horn, P.L. (1994a). Trawl survey of hoki and middle depth species on the Chatham Rise, December 1991–January 1992 (TAN9106). *New Zealand Fisheries Data Report 43*. 38 p.
Horn, P.L. (1994b). Trawl survey of hoki and middle depth species on the Chatham Rise, December 1992–January 1993 (TAN9212). *New Zealand Fisheries Data Report 44*. 43 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(3)*: 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. *New Zealand Fisheries Assessment Report 2013/31.* 58 p.
Horn, P.L. (2015). Southern hake (*Merluccius australis*) in New Zealand: biology, fisheries and stock assessment, pp. 101–125. *In* Arancibia, H. (Ed.), Hakes: Biology and exploitation. *Wiley-Blackwell Fish and Aquatic Resources Series 17.*

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.* 74 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.

Horn, P.L.; Sutton, C.P. (2019). Catch-at-age for hake (*Merluccius australis*) and ling (*Genypterus blacodes*) in the 2016–17 fishing year and from a trawl survey in 2018, with a summary of all available data sets from the New Zealand EEZ. *New Zealand Fisheries Assessment Report 2019/12.* 80 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.

Livingston, M.E.; Bull, B.; Stevens, D.W.; Bagley, N.W. (2002). A review of hoki and middle depths trawl surveys of the Chatham Rise, January 1992–2001. *New Zealand Fisheries Assessment Report 2002/48*. 69 p.

Livingston, M.E.; Stevens, D.W. (2005). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2004 (TAN0401). *New Zealand Fisheries Assessment Report 2005/21*. 62 p.

Livingston, M.E.; Stevens, D.W.; O'Driscoll, R.L.; Francis, R.I.C.C. (2004). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2003 (TAN0301). *New Zealand Fisheries Assessment Report 2004/16*. 71 p.

McGregor, V. (in press). Chatham Rise hake (*Merluccius australis*) 1989–90 to 2018–19: Descriptive analysis of the commercial catch effort data and standardised catch and effort analysis (CPUE). New Zealand Fisheries Assessment Report.

Schnute, J. (1981). A versatile growth model with statistically stable parameters. *Canadian Journal of Fisheries and Aquatic Sciences 38*: 1128–1140.

Schofield, K.A.; Horn, P.L. (1994). Trawl survey of hoki and middle depth species on the Chatham Rise, January 1994 (TAN9401). *New Zealand Fisheries Data Report 53*. 54 p.

Schofield, K.A.; Livingston, M.E. (1995). Trawl survey of hoki and middle depth species on the Chatham Rise, January 1995 (TAN9501). *New Zealand Fisheries Data Report 59*. 53 p.

Schofield, K.A.; Livingston, M.E. (1996). Trawl survey of hoki and middle depth species on the Chatham Rise, January 1996 (TAN9601). *New Zealand Fisheries Data Report 71*. 50 p.

Schofield, K.A.; Livingston, M.E. (1997). Trawl survey of hoki and middle depth species on the Chatham Rise, January 1997 (TAN9701). *NIWA Technical Report 6*. 50 p.

Shertzer, K.W.; Conn, P.B. (2012). Spawner-Recruit Relationships of Demersal Marine**:** Prior distribution of steepness. *Bulletin of Marine Science 88*: 39–50.

Stevens, D.W.; Livingston, M.E. (2003). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2002 (TAN0201). *New Zealand Fisheries Assessment Report 2003/19*. 57 p.

Stevens, D.W.; Livingston, M.E.; Bagley, N.W. (2001). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2000 (TAN0001). *NIWA Technical Report 104*. 55 p.

Stevens, D.W.; Livingston, M.E.; Bagley, N.W. (2002). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2001 (TAN0101). *NIWA Technical Report 116*. 61 p.

Stevens, D.W.; O'Driscoll, R.L. (2006). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2005 (TAN0501). *New Zealand Fisheries Assessment Report 2006/13*. 73 p.

Stevens, D.W.; O'Driscoll, R.L. (2007). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2006 (TAN0601). *New Zealand Fisheries Assessment Report 2007/5*. 73 p.

Stevens, D.W.; O'Driscoll, R.L.; Gauthier, S. (2008). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2007 (TAN0701). *New Zealand Fisheries Assessment Report 2008/52*. 81 p.

Stevens, D.W.; O'Driscoll, R.L.; Horn, P.L. (2009a). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2008 (TAN0801). *New Zealand Fisheries Assessment Report 2009/18*. 86 p.

Stevens, D.W.; O'Driscoll, R.L.; Horn, P.L. (2009b). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2009 (TAN0901). *New Zealand Fisheries Assessment Report 2009/55*. 91 p.

Stevens, D.W.; O'Driscoll, R.L.; Dunn, M.R.; MacGibbon, D.; Horn, P.L.; Gauthier, S. (2011). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2010 (TAN1001). *New Zealand Fisheries Assessment Report 2011/10*. 112 p.

Stevens, D.W.; O'Driscoll, R.L.; Dunn, M.R.; Ballara, S.L.; Horn, P.L. (2012). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2011 (TAN1101). *New Zealand Fisheries Assessment Report 2012/10*. 98 p.

Stevens, D.W.; O'Driscoll, R.L.; Dunn, M.R.; Ballara, S.L.; Horn, P.L. (2013). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2012 (TAN1201). *New Zealand Fisheries Assessment Report 2013/34*. 103 p.

Stevens, D.W.; O'Driscoll, R.L.; Oeffner, J.; Ballara, S.L.; Horn, P.L. (2014). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2013 (TAN1301). *New Zealand Fisheries Assessment Report 2014/02*. 110 p.

Stevens, D.W.; O'Driscoll, R.L.; Ladroit, Y.; Ballara, S.L.; MacGibbon, D.J.; Horn, P.L. (2015). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2014 (TAN1401). *New Zealand Fisheries Assessment Report 2015/19*. 119 p.

Stevens, D.W.; O'Driscoll, R.L.; Ballara, S.L.; Ladroit, Y. (2017). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2016 (TAN1601). *New Zealand Fisheries Assessment Report 2017/8*. 131 p.

Stevens, D.W.; O'Driscoll, R.L.; Ballara, S.L.; Schimel, A.C.G. (2018). Trawl survey of hoki and middle-depth species on the Chatham Rise, January 2018 (TAN1801). *New Zealand Fisheries Assessment Report 2018/41*. 115 p.

Stevens, D.W.; O'Driscoll, R.L.; Ballara, S.L.; Schimel, A.C.G. (in press). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2020 (TAN2001). New Zealand Fisheries Assessment Report.

APPENDIX A: RESOURCE SURVEY BIOMASS INDICES FOR HAKE IN HAK 4

Table A1: Biomass indices (t) and coefficients of variation (CV) for hake from resource surveys of the Chatham Rise. (These estimates assume that the areal availability, vertical availability, and vulnerability are equal to one.)

Vessel[1]	Date	Trip code	Depth	Biomass	CV	Reference
Shinkai Maru	Mar 1983	SHI8301	200–800	11 327	0.12	N.W. Bagley, NIWA, pers. comm.
Shinkai Maru[2]	Nov–Dec 1983	SHI8304	200–800	8 160	0.12	N.W. Bagley, NIWA, pers. comm.
Shinkai Maru	Jul 1986	SHI8602	200–800	7 630	0.13	N.W. Bagley, NIWA, pers. comm.
Amaltal Explorer	Nov–Dec 1989	AEX8903	200–800	3 576	0.19	N.W. Bagley, NIWA, pers. comm.
Tangaroa	Jan 1992	TAN9106	200–800	4 180	0.15	Horn 1994a
Tangaroa	Jan 1993	TAN9212	200–800	2 950	0.17	Horn 1994b
Tangaroa	Jan 1994	TAN9401	200–800	3 353	0.10	Schofield & Horn 1994
Tangaroa	Jan 1995	TAN9501	200–800	3 303	0.23	Schofield & Livingston 1995
Tangaroa	Jan 1996	TAN9601	200–800	2 457	0.13	Schofield & Livingston 1996
Tangaroa	Jan 1997	TAN9701	200–800	2 811	0.17	Schofield & Livingston 1997
Tangaroa	Jan 1998	TAN9801	200–800	2 873	0.18	Bagley & Hurst 1998
Tangaroa	Jan 1999	TAN9901	200–800	2 302	0.12	Bagley & Livingston 2000
Tangaroa	Jan 2000	TAN0001	200–800	2 090	0.09	Stevens et al. 2001
			200–1000	2 152	0.09	Stevens et al. 2001
Tangaroa	Jan 2001	TAN0101	200–800	1 589	0.13	Stevens et al. 2002
Tangaroa	Jan 2002	TAN0201	200–800	1 567	0.15	Stevens & Livingston 2003
			200–1000	1 905	0.13	Stevens & Livingston 2003
Tangaroa	Jan 2003	TAN0301	200–800	888	0.16	Livingston et al. 2004
Tangaroa	Jan 2004	TAN0401	200–800	1 547	0.17	Livingston & Stevens 2005
Tangaroa	Jan 2005	TAN0501	200–800	1 048	0.18	Stevens & O'Driscoll 2006
Tangaroa	Jan 2006	TAN0601	200–800	1 384	0.19	Stevens & O'Driscoll 2007
Tangaroa	Jan 2007	TAN0701	200–800	1 824	0.12	Stevens et al. 2008
			200–1000	1 976	0.12	Stevens et al. 2008
Tangaroa	Jan 2008	TAN0801	200–800	1 257	0.13	Stevens et al. 2009a
			200–1000	1 323	0.13	Stevens et al. 2009a
Tangaroa	Jan 2009	TAN0901	200–800	2 419	0.21	Stevens et al. 2009b
Tangaroa	Jan 2010	TAN1001	200–800	1 701	0.25	Stevens et al. 2011
			200–1300	1 862	0.25	Stevens et al. 2011

Table A1 continued.

Vessel[1]	Date	Trip code	Depth	Biomass	CV	Reference
Tangaroa	Jan 2011	TAN1101	200–800	1 099	0.15	Stevens et al. 2012
			200–1300	1 201	0.14	Stevens et al. 2012
Tangaroa	Jan 2012	TAN1201	200–800	1 292	0.15	Stevens et al. 2013
			200–1300	1 493	0.13	Stevens et al. 2013
Tangaroa	Jan 2013	TAN1301	200–800	1 793	0.15	Stevens et al. 2014
			200–1300	1 874	0.15	Stevens et al. 2014
Tangaroa	Jan 2014	TAN1401	200–800	1 377	0.15	Stevens et al. 2015
			200–1300	1 510	0.14	Stevens et al. 2015
Tangaroa	Jan 2016	TAN1601	200–800	1 299	0.19	Stevens et al. 2017
			200–1300	1 512	0.16	Stevens et al. 2017
Tangaroa	Jan 2018	TAN1801	200–800	1 660	0.34	Stevens et al. 2018
			200–1300	1 813	0.32	Stevens et al. 2018
Tangaroa	Jan 2020	TAN2001	200–800	1 037	0.20	Stevens et al. (in press)
			200–1300			

1. Although surveys by *Wesermünde* were carried out on the Chatham Rise in 1979, biomass estimates for hake were not calculated.
2. East of 176º E only.

APPENDIX B: MPD FITS TO COMPOSITION DATA

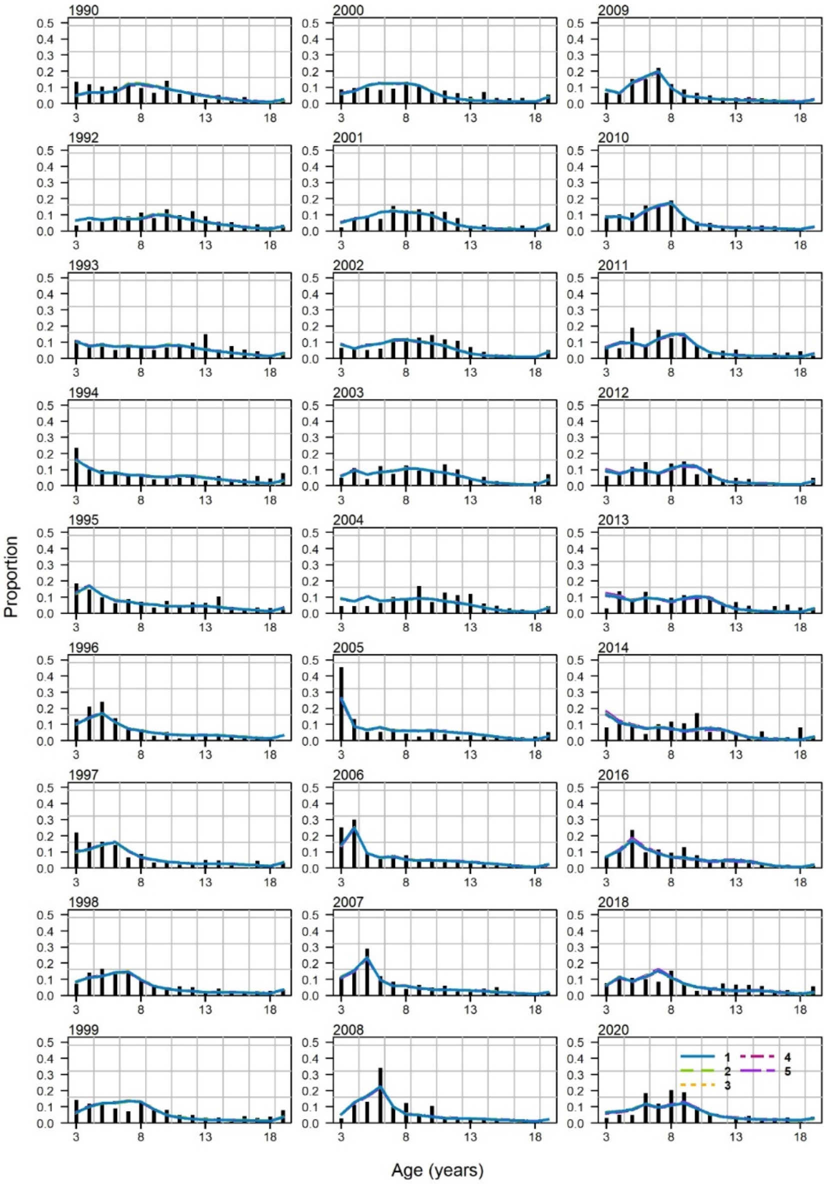

Figure B1: MPD fits to trawl survey proportion-at-age data for model runs (1) Base, (2) Old base, (3) High *M*, (4) Low *M*, and (5) CPUE-east. Note fits to all models are essentially identical, so only the (blue) fit to model 1 is apparent.

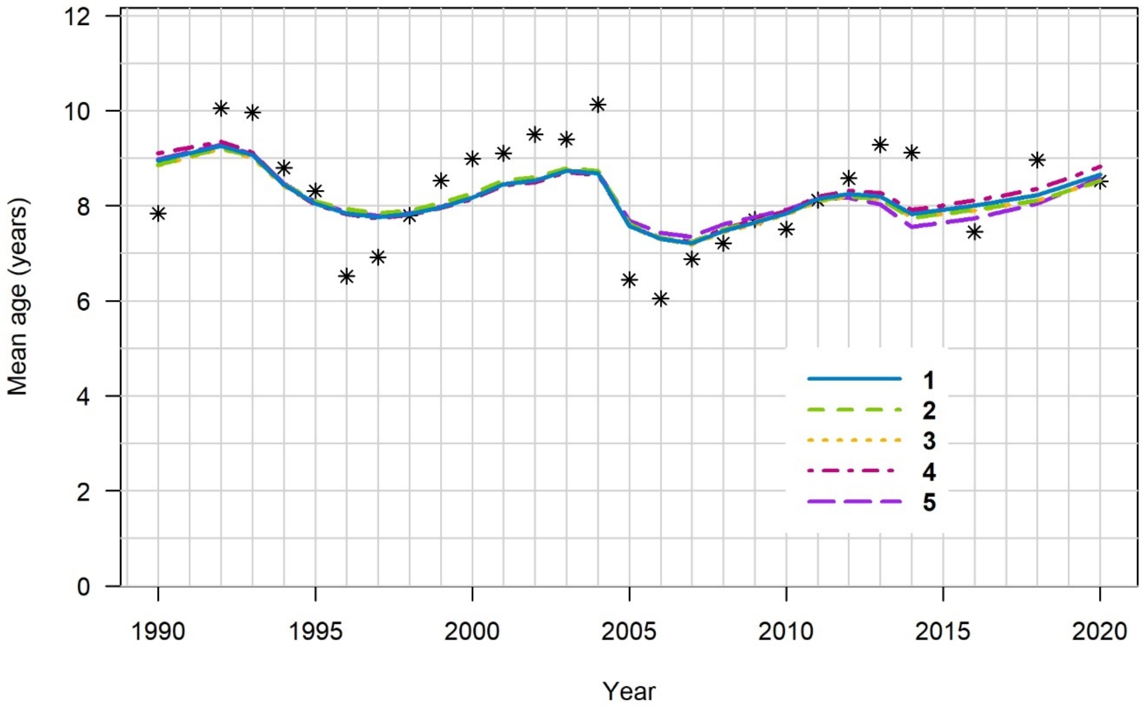

Figure B2: MPD fits to trawl survey mean age data for model runs (1) Base, (2) Old base, (3) High *M*, (4) Low *M*, and (5) CPUE-east.

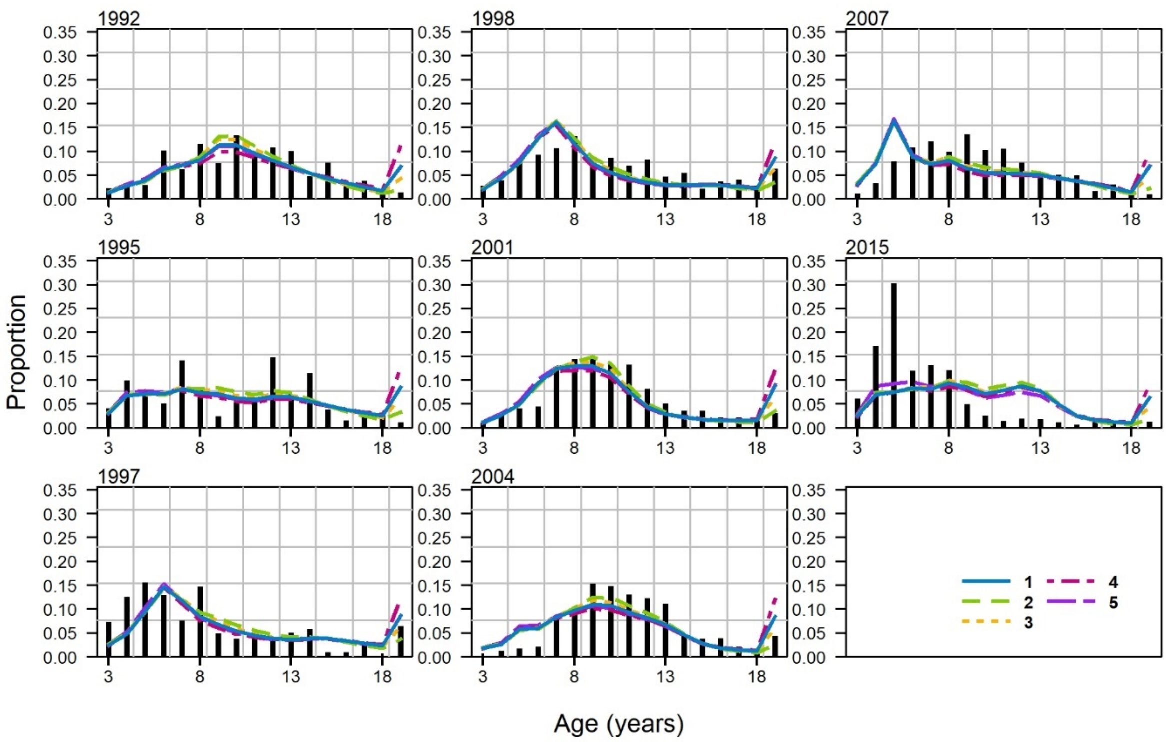

Figure B3: MPD fits to eastern trawl fishery proportion-at-age data for model runs (1) Base, (2) Old base, (3) High *M*, (4) Low *M*, and (5) CPUE-east.

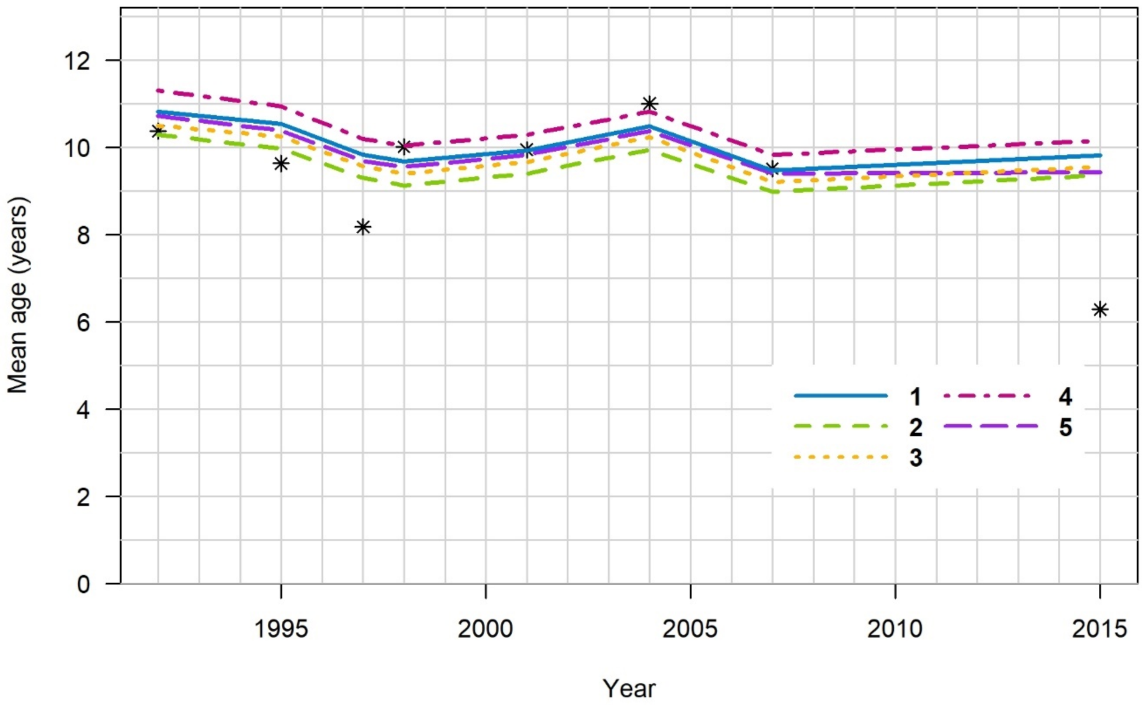

Figure B4: MPD fits to eastern trawl fishery mean age data for model runs (1) Base, (2) Old base, (3) High *M*, (4) Low *M*, and (5) CPUE-east.

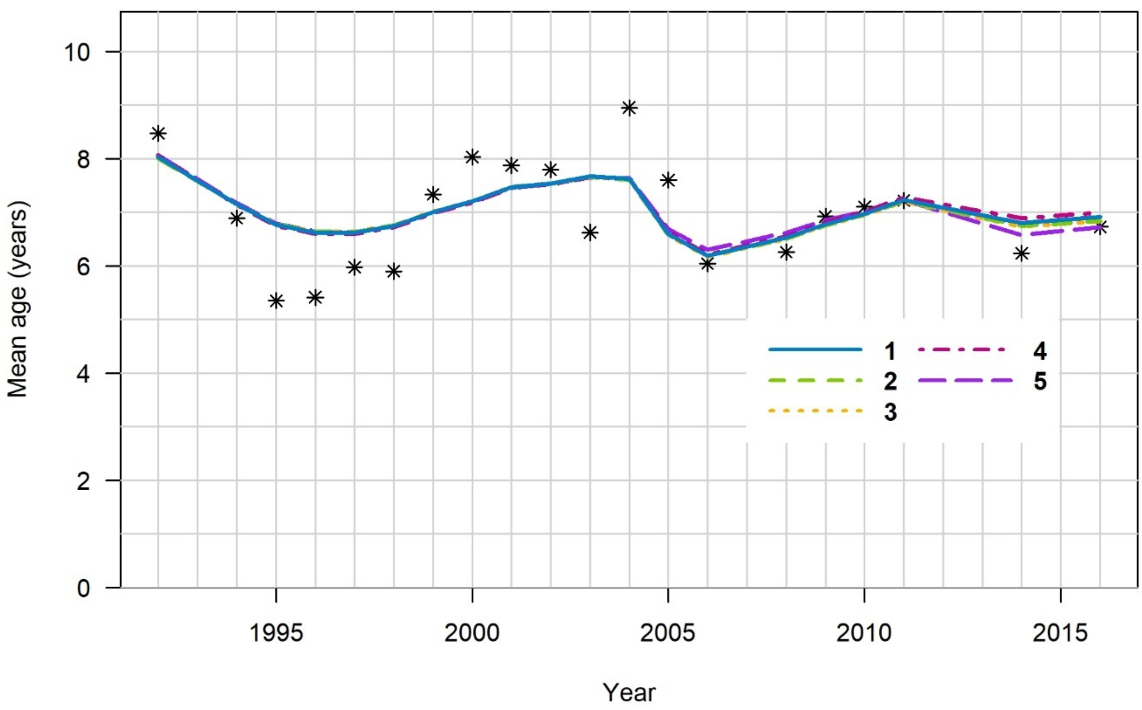

Figure B5: MPD fits to western trawl fishery mean age data for model runs (1) Base, (2) Old base, (3) High *M*, (4) Low *M*, and (5) CPUE-east.

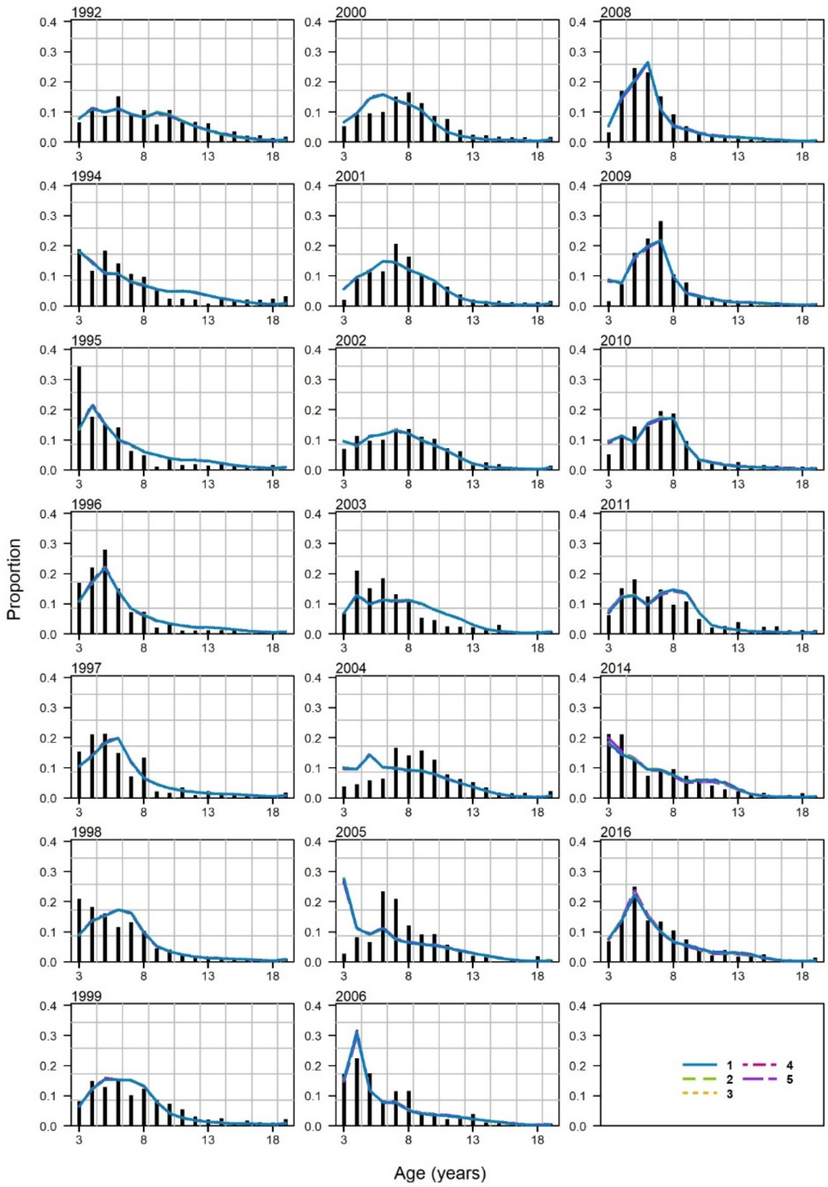

Figure B6: MPD fits to western trawl fishery proportion-at-age data for model runs (1) Base, (2) Old base, (3) High *M*, (4) Low *M*, and (5) CPUE-east.

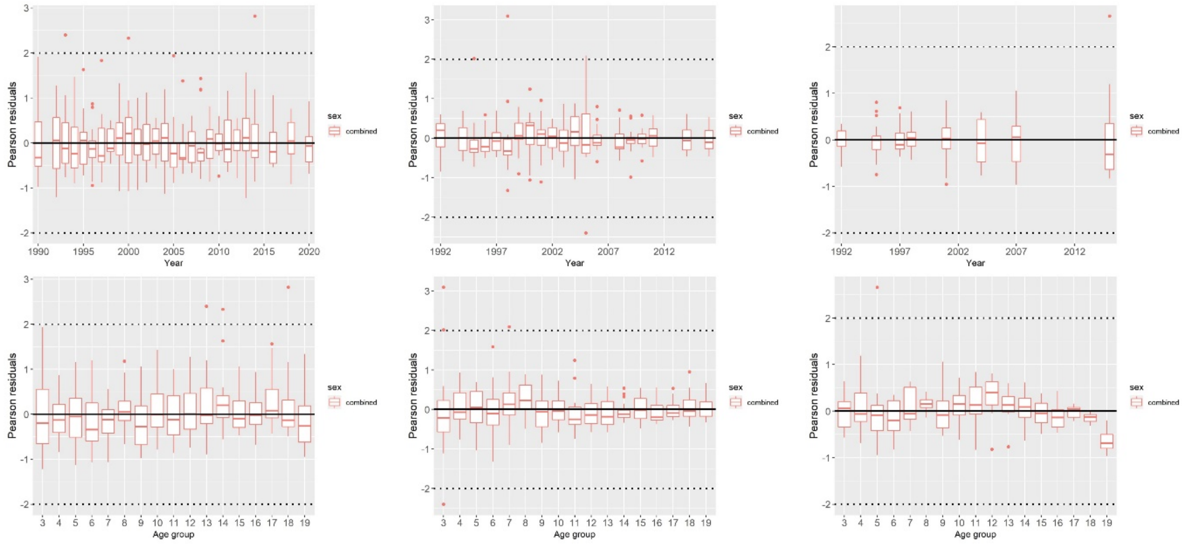

Figure B7: Pearson residuals on fitting to proportions at age from the trawl survey (left) west fishery (middle), and east fishery (right); Base run.

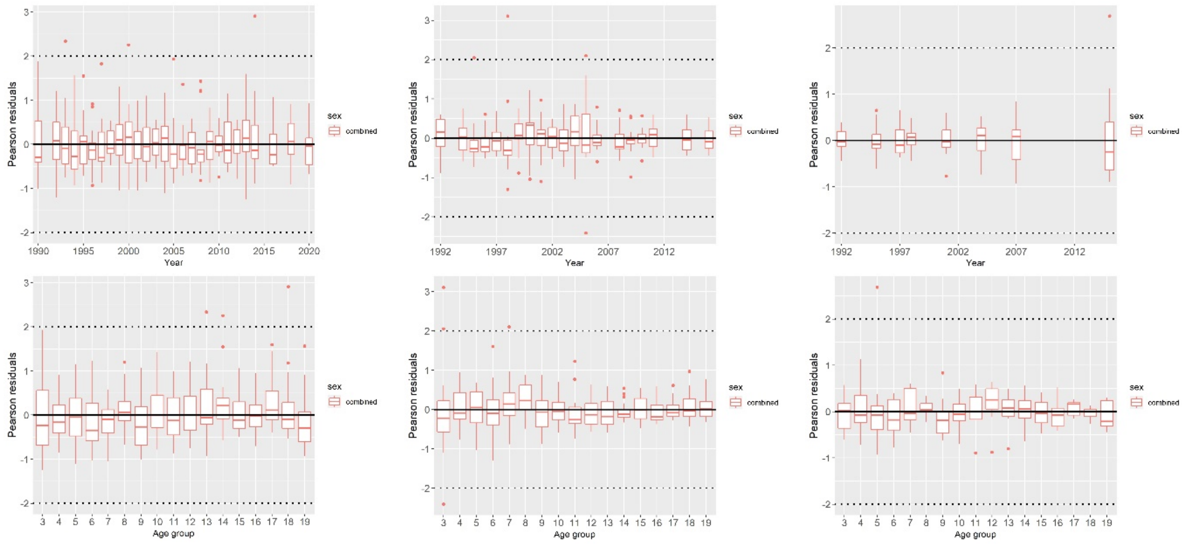

Figure B8: Pearson residuals on fitting to proportions at age from the trawl survey (left) west fishery (middle), and east fishery (right); 'Old Base' run (all selectivities double normal).

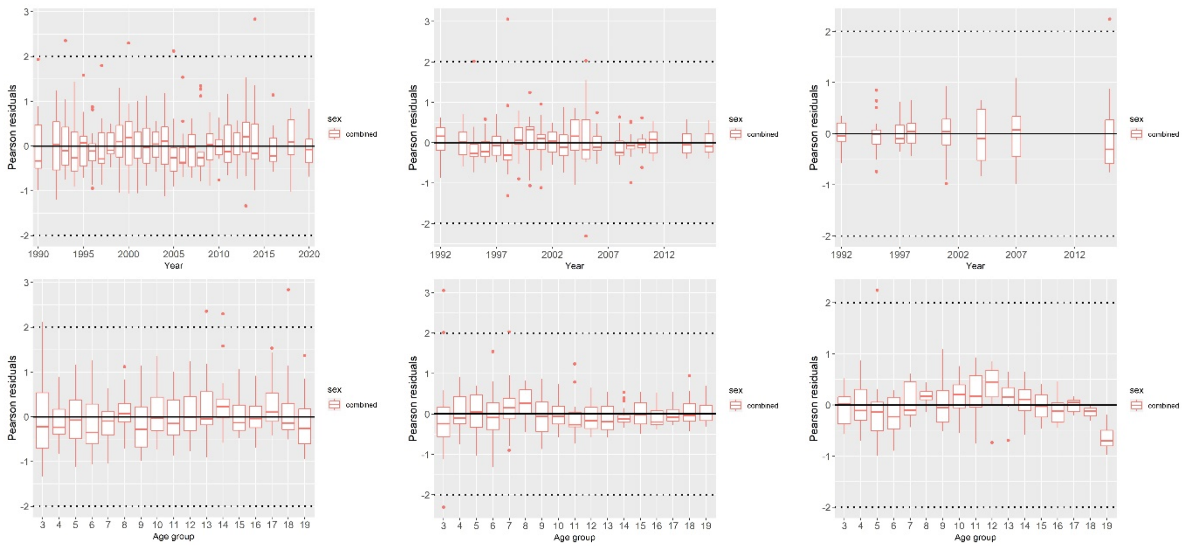

Figure B9: Pearson residuals on fitting to proportions at age from the trawl survey (left) west fishery (middle) and east fishery (right); 'CPUE-east' run.

APPENDIX C: MCMC CONVERGENCE AND DISTRIBUTION PLOTS

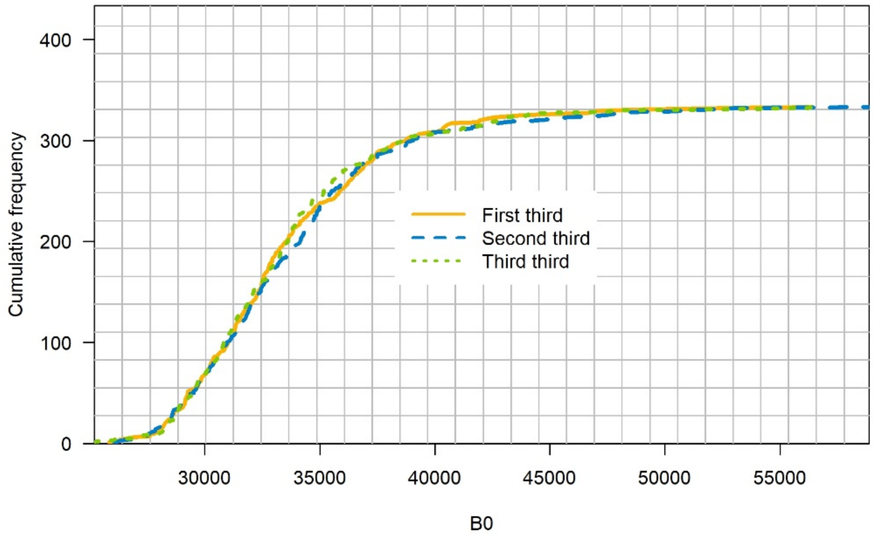

Figure C1: MCMC cumulative frequencies of B_0 for the first (solid gold line), second (dashed blue line) and third (dotted green line) third of the MCMC chain for Base model run. The chain is that obtained after MCMC is re-started using covariance matrix calculated from the initial MCMC run.

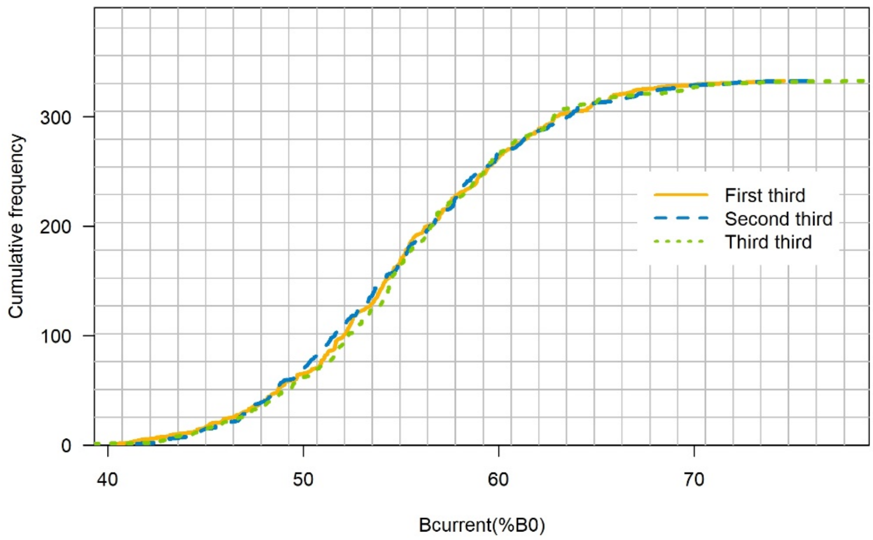

Figure C2: MCMC cumulative frequencies of $B_{current}$(% B_0) for the first (solid gold line), second (dashed blue line) and third (dotted green line) third of the MCMC chain for Base model run. The chain is that obtained after MCMC is re-started using covariance matrix calculated from the initial MCMC run.

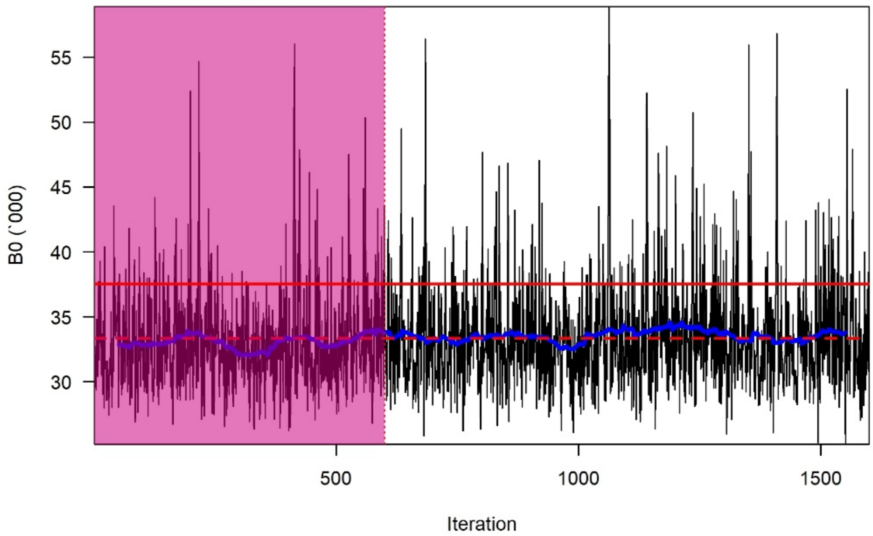

Figure C3: Trace diagnostic plot of the MCMC chain for B_0 in the Base model run. The red dashed line is the mean of the entire chain, the blue line is the moving mean of 100 points of the chain. The solid red line shows the value obtained from the MPD run. The chain is that obtained after MCMC is re-started using covariance matrix calculated from the initial MCMC run. The shaded area shows the outputs removed when forming the posterior probability distribution.

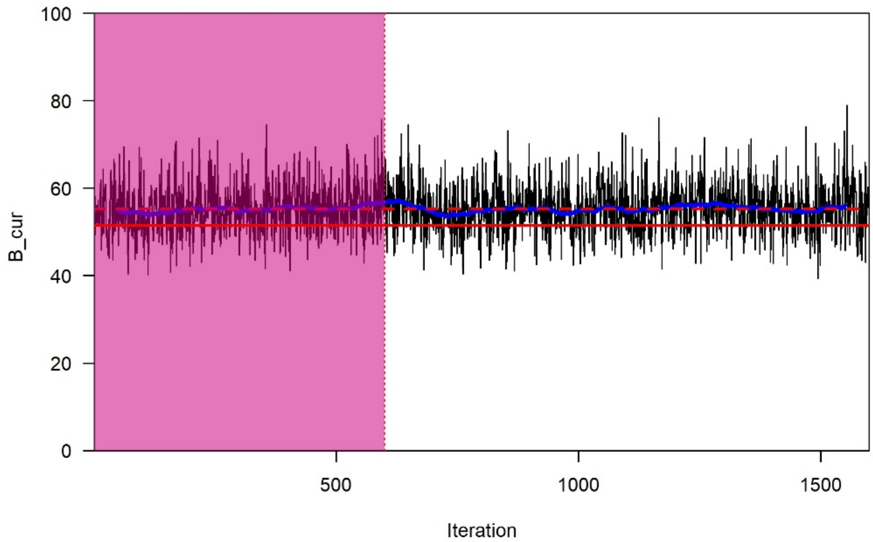

Figure C4: Trace diagnostic plot of the MCMC chain for $B_{current}$(% B_0) in the Base model run. The red dashed line is the mean of the entire chain, the blue line is the moving mean of 100 points of the chain. The solid red line shows the value obtained from the MPD run. The chain is that obtained after MCMC is re-started using covariance matrix calculated from the initial MCMC run. The shaded area shows the outputs removed when forming the posterior probability distribution.

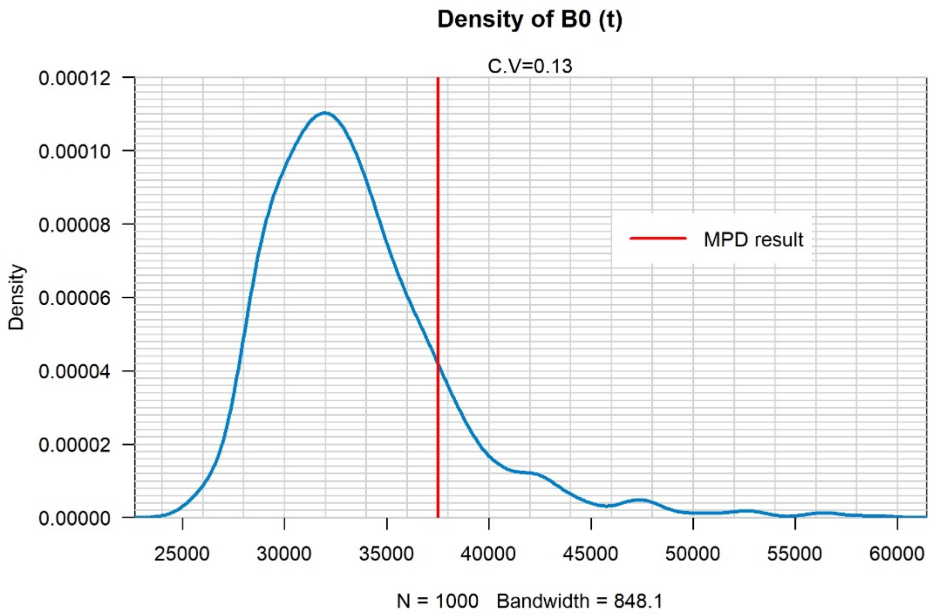

Figure C5: Estimated posterior distribution for B_0 in Base model run.

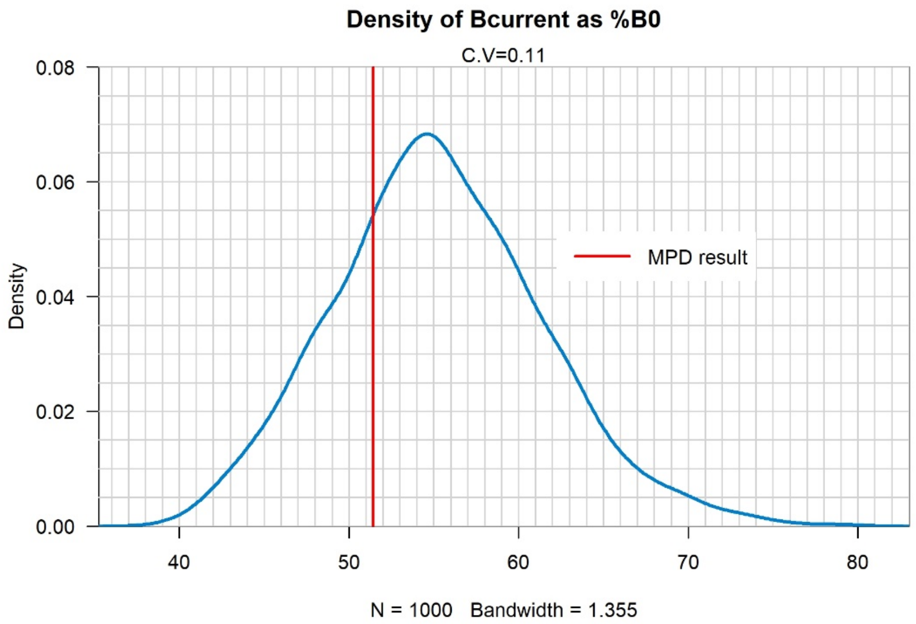

Figure C6: Estimated posterior distribution for $B_{current}$(% B_0) in Base model run.

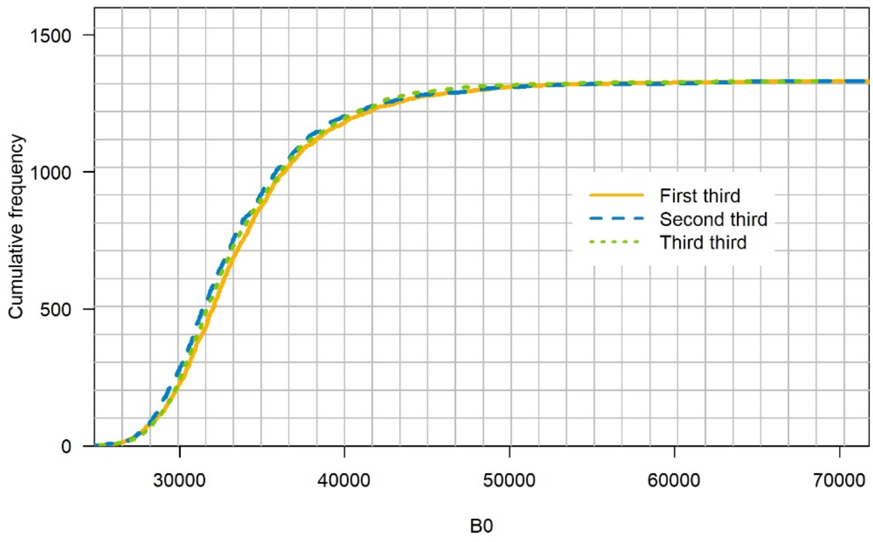

Figure C7: MCMC cumulative frequencies of B_0 for the first (solid gold line), second (dashed blue line), and third (dotted green line) third of the MCMC chain for run with all selectivities set to double normal. The chain is that obtained after MCMC is re-started using covariance matrix calculated from the initial MCMC run.

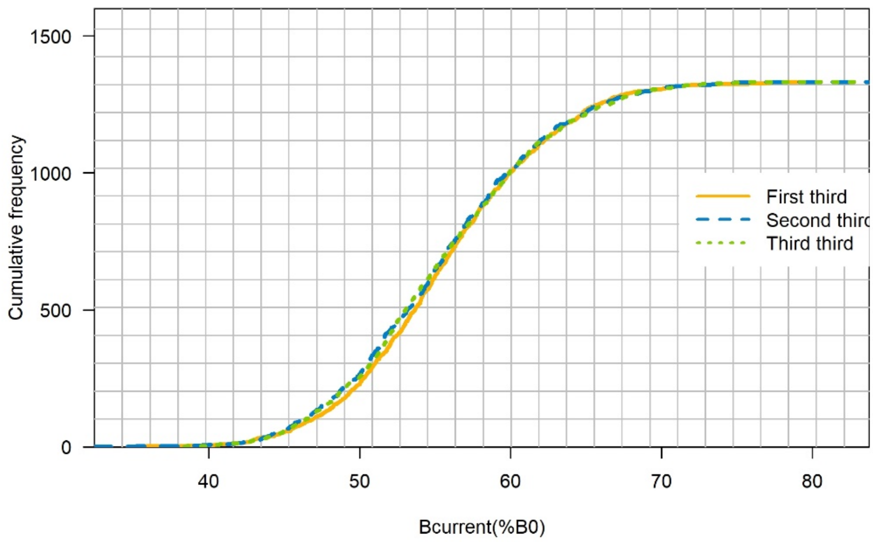

Figure C8: MCMC cumulative frequencies of $B_{current}$(% B_0) for the first (solid gold line), second (dashed blue line), and third (dotted green line) third of the MCMC chain for run with all selectivities set to double normal. The chain is that obtained after MCMC is re-started using covariance matrix calculated from the initial MCMC run.

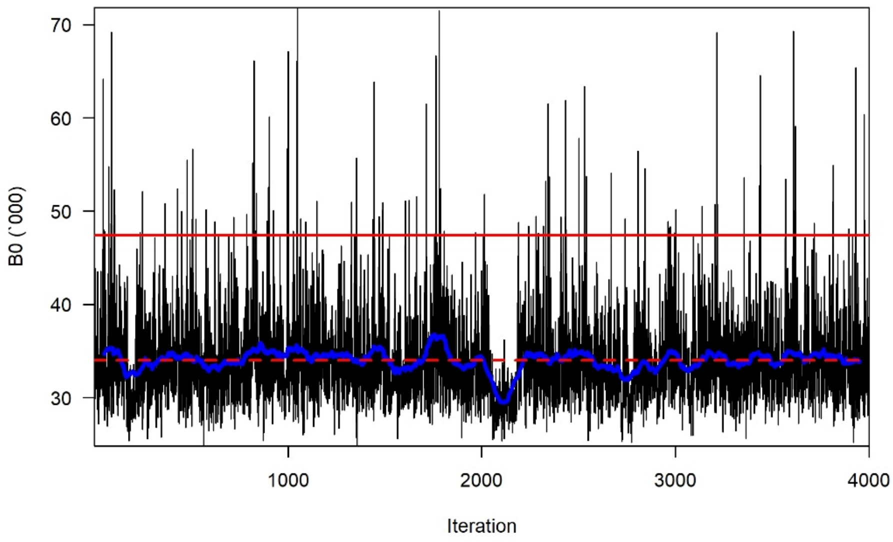

Figure C9: Trace diagnostic plot of the MCMC chain for B_0 in the run with all selectivities set to double normal. The red dashed line is the mean of the entire chain, the blue line is the moving mean of 100 points of the chain. The solid red line shows the value obtained from the MPD run. The chain is that obtained after MCMC is re-started using covariance matrix calculated from the initial MCMC run. It was not considered necessary to remove outputs when forming the posterior probability distribution.

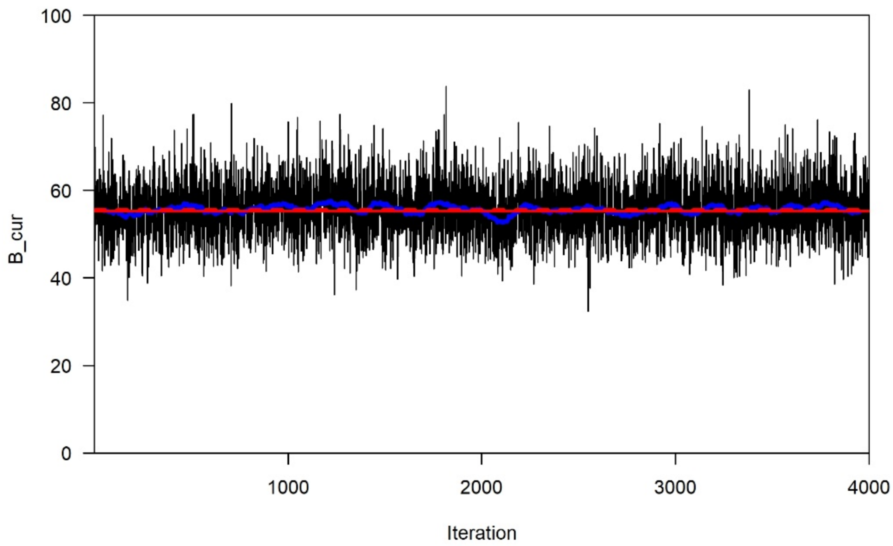

Figure C10: Trace diagnostic plot of the MCMC chain for $B_{current}$(% B_0) in the run with all selectivities set to double normal. The red dashed line is the mean of the entire chain, the blue line is the moving mean of 100 points of the chain. The solid red line shows the value obtained from the MPD run. The chain is that obtained after MCMC is re-started using covariance matrix calculated from the initial MCMC run. It was not considered necessary to remove outputs when forming the posterior probability distribution.

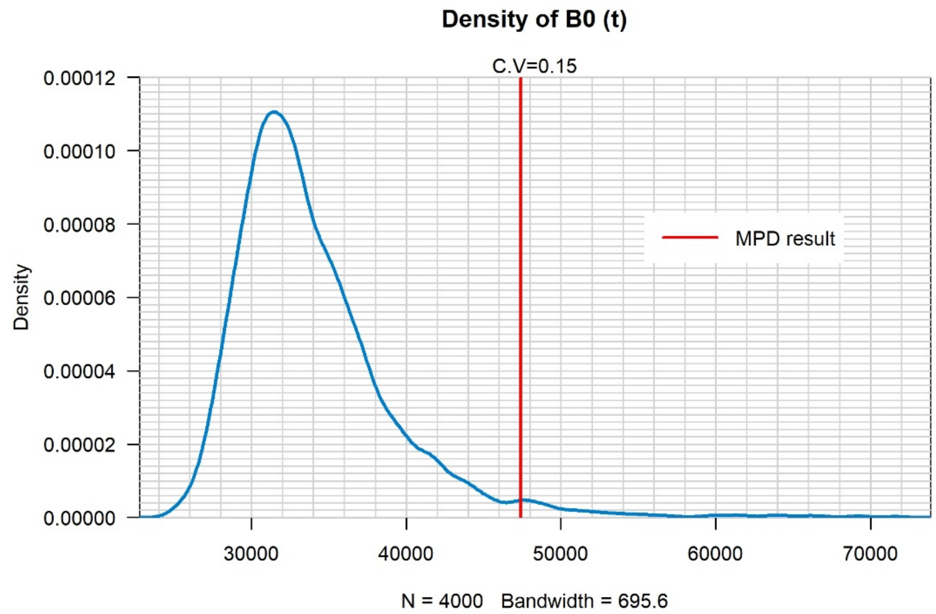

Figure C11: Estimated posterior distribution for B_0 in run with all selectivities set to double normal.

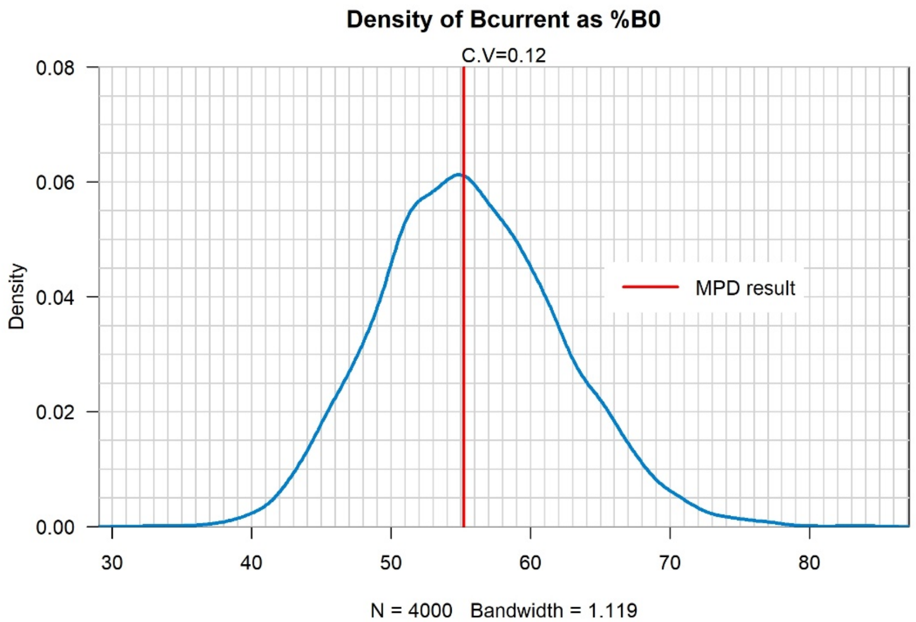

Figure C12: Estimated posterior distribution for $B_{current}$(% B_0) in run with all selectivities set to double normal.

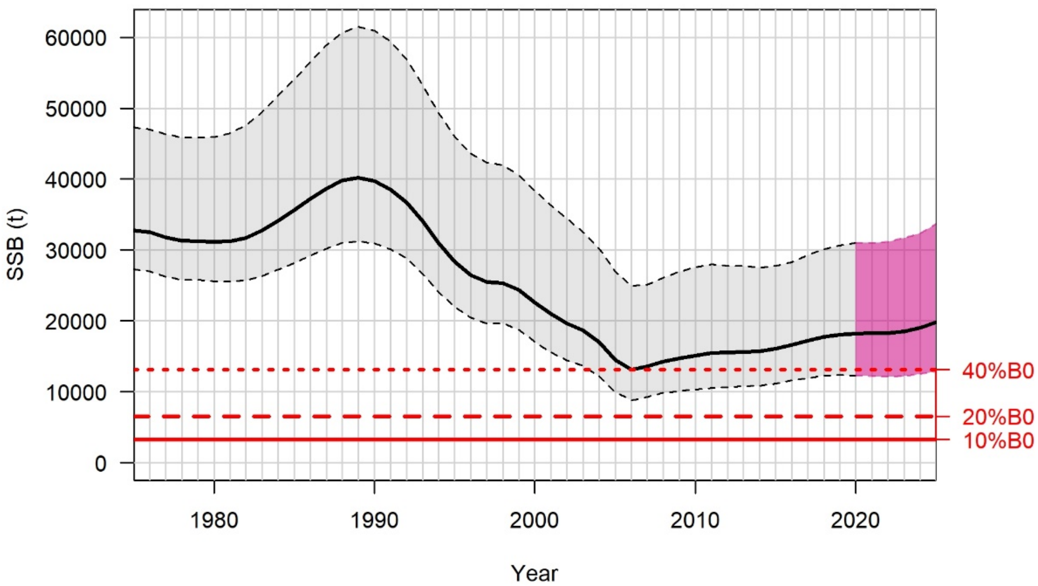

Figure C13: Projection using MCMC. 'Old base' run (all selectivities double normal) using all estimated year class strengths to estimate future year class strengths. Future catch option: Average last 6 years.

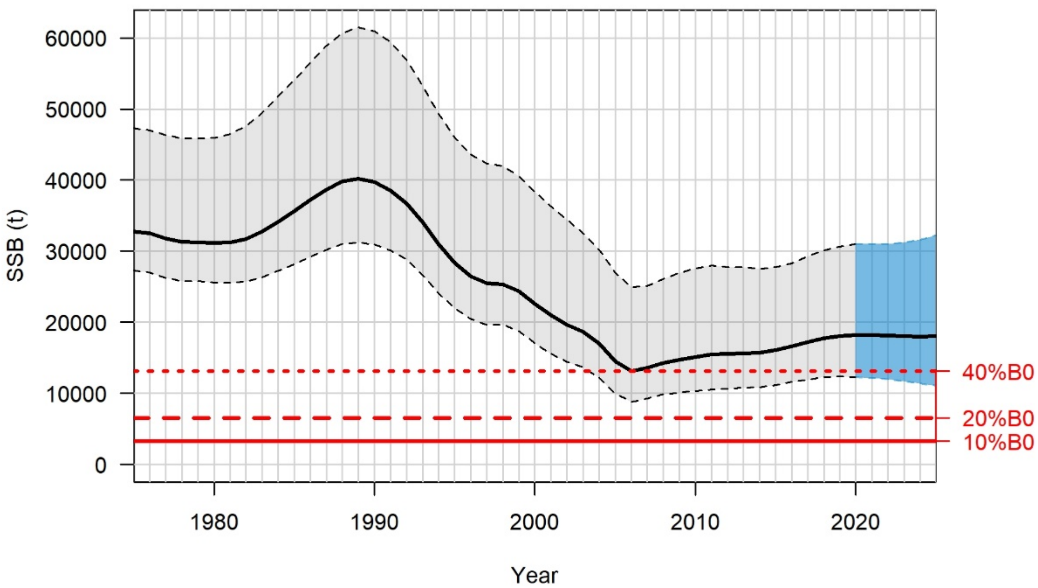

Figure C14: Projection using MCMC. 'Old base' run (all selectivities double normal) using most recent 10 estimated year class strengths to estimate future year class strengths. Future catch option: Average last 6 years.

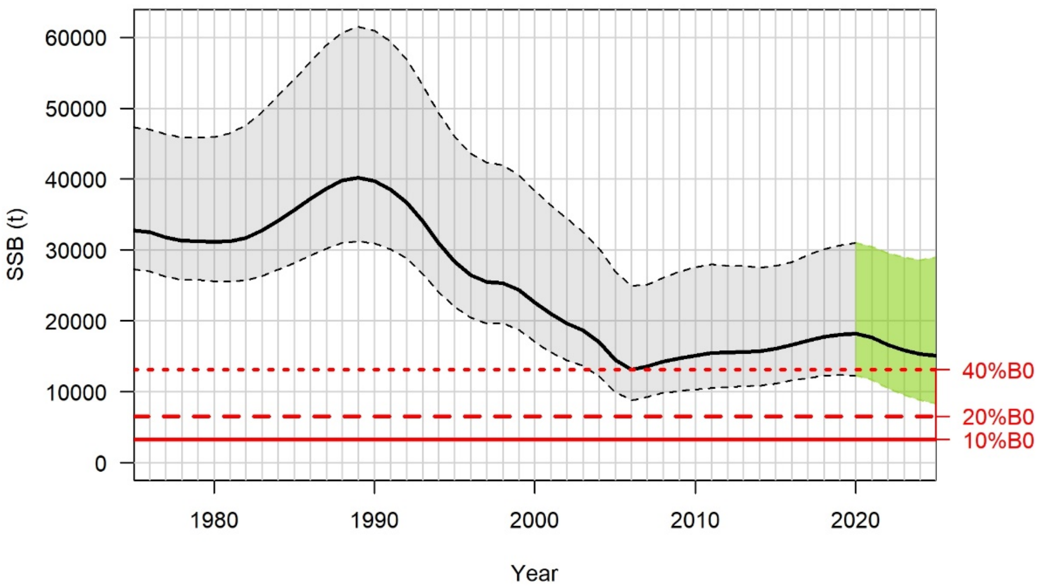

Figure C15: Projection using MCMC. 'Old base' run (all selectivities double normal) using all estimated year class strengths to estimate future year class strengths. Future catch option: TACC.

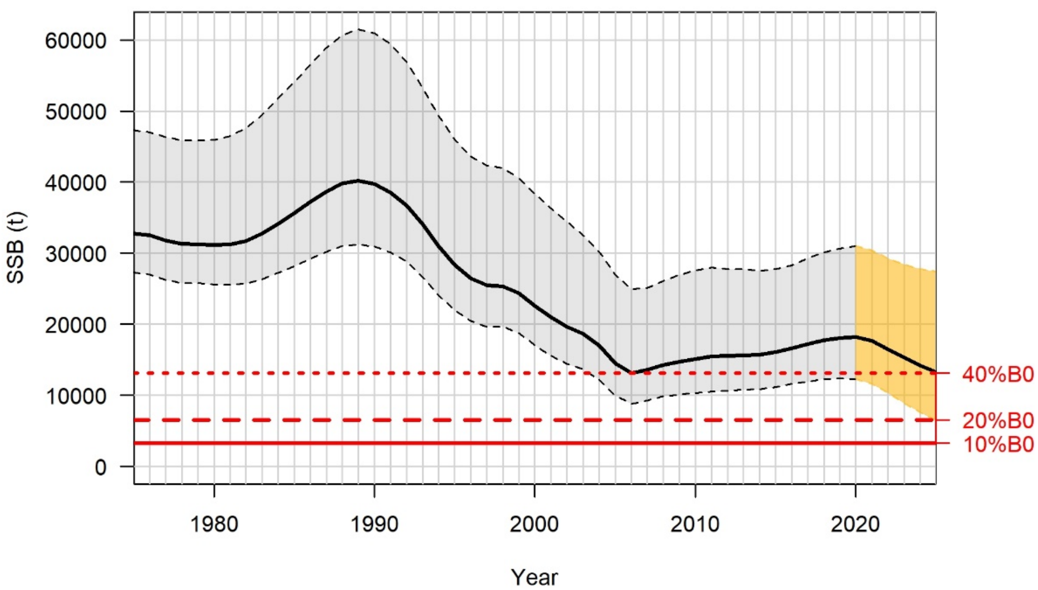

Figure C16: Projection using MCMC. 'Old base' run (all selectivities double normal) using most recent 10 estimated year class strengths to estimate future year class strengths. Future catch option: TACC.

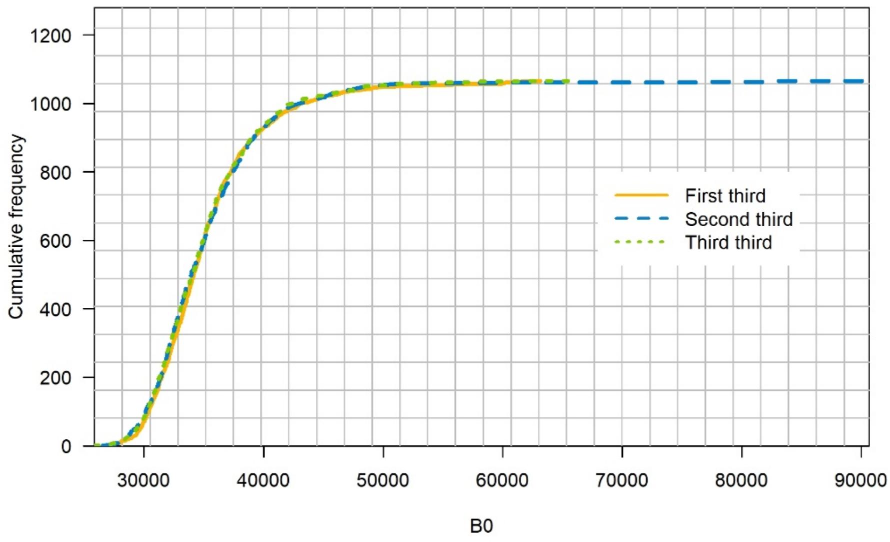

Figure C17: MCMC cumulative frequencies of B_0 for the first (solid gold line), second (dashed blue line), and third (dotted green line) third of the MCMC chain for 'CPUE-east' run. The chain is that obtained after MCMC is re-started using covariance matrix calculated from the initial MCMC run.

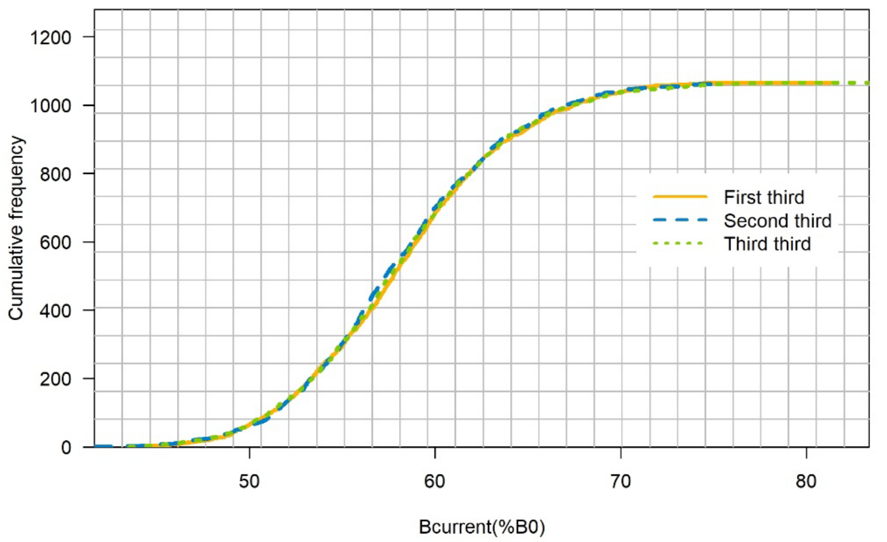

Figure C18: MCMC cumulative frequencies of $B_{current}$(% B_0) for the first (solid gold line), second (dashed blue line) and third (dotted green line) third of the MCMC chain for 'CPUE-east' run. The chain is that obtained after MCMC is re-started using covariance matrix calculated from the initial MCMC run.

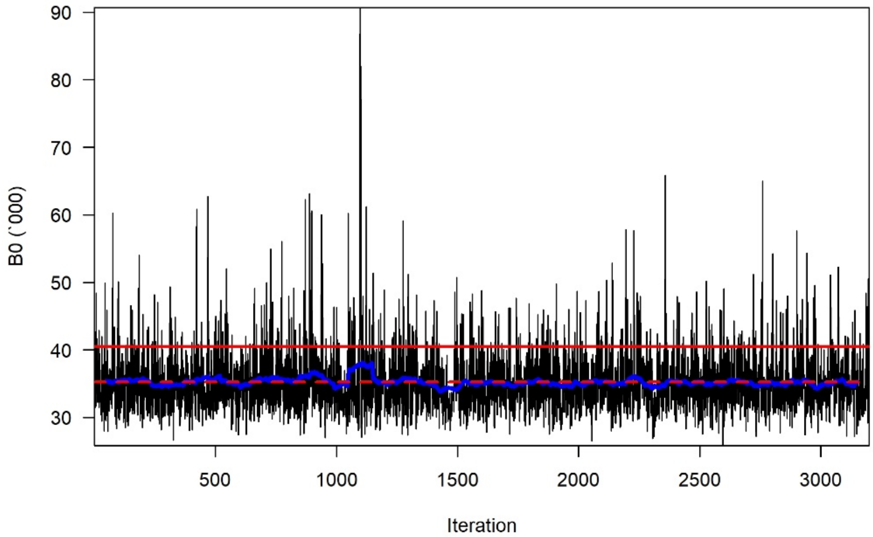

Figure C19: Trace diagnostic plot of the MCMC chain for B_0 in the 'CPUE-east' run. The red dashed line is the mean of the entire chain, the blue line is the moving mean of 100 points of the chain. The solid red line shows the value obtained from the MPD run. The chain is that obtained after MCMC is re-started using covariance matrix calculated from the initial MCMC run. It was not considered necessary to remove outputs when forming the posterior probability distribution.

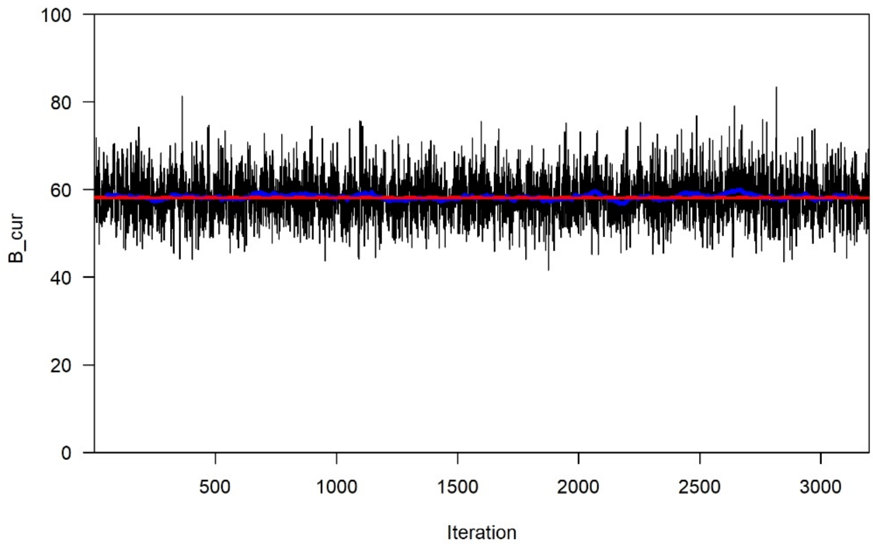

Figure C20: Trace diagnostic plot of the MCMC chain for $B_{current}$(% B_0) in the 'CPUE-east' run. The red dashed line is the mean of the entire chain, the blue line is the moving mean of 100 points of the chain. The solid red line shows the value obtained from the MPD run. The chain is that obtained after MCMC is re-started using covariance matrix calculated from the initial MCMC run. It was not considered necessary to remove outputs when forming the posterior probability distribution.

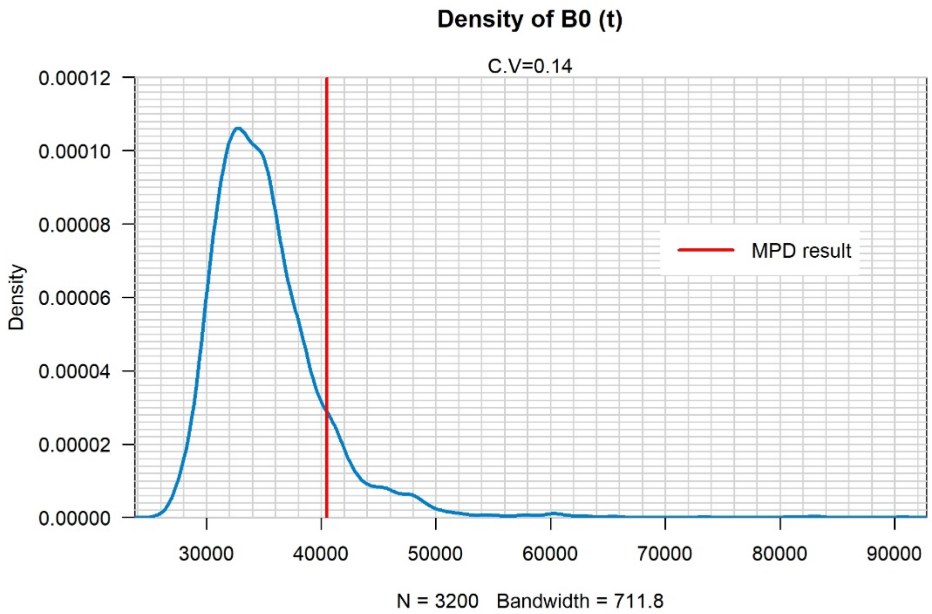

Figure C21: Estimated posterior distribution for B_0 in 'CPUE-east' run.

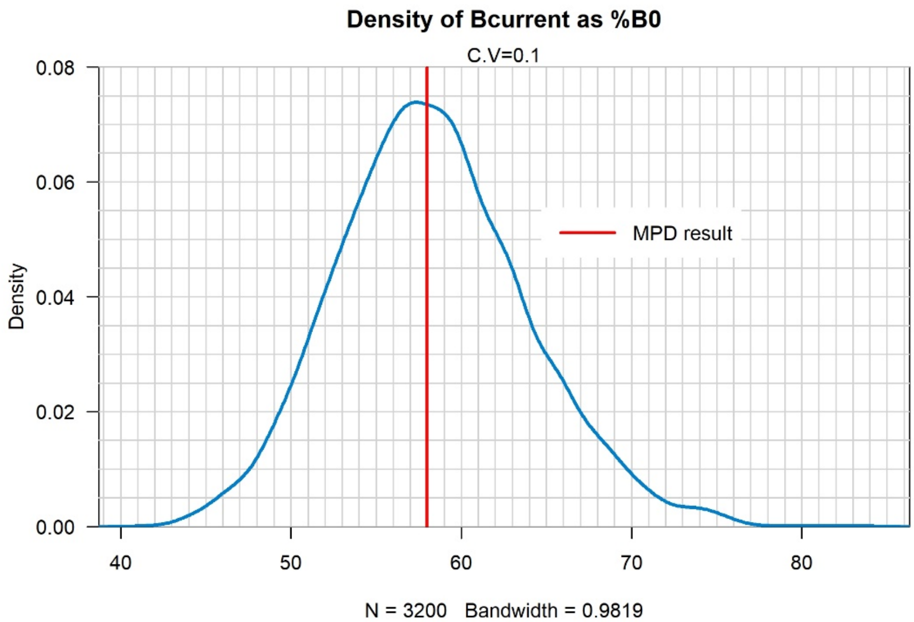

Figure C22: Estimated posterior distribution for $B_{current}$(% B_0) in 'CPUE-east' run.

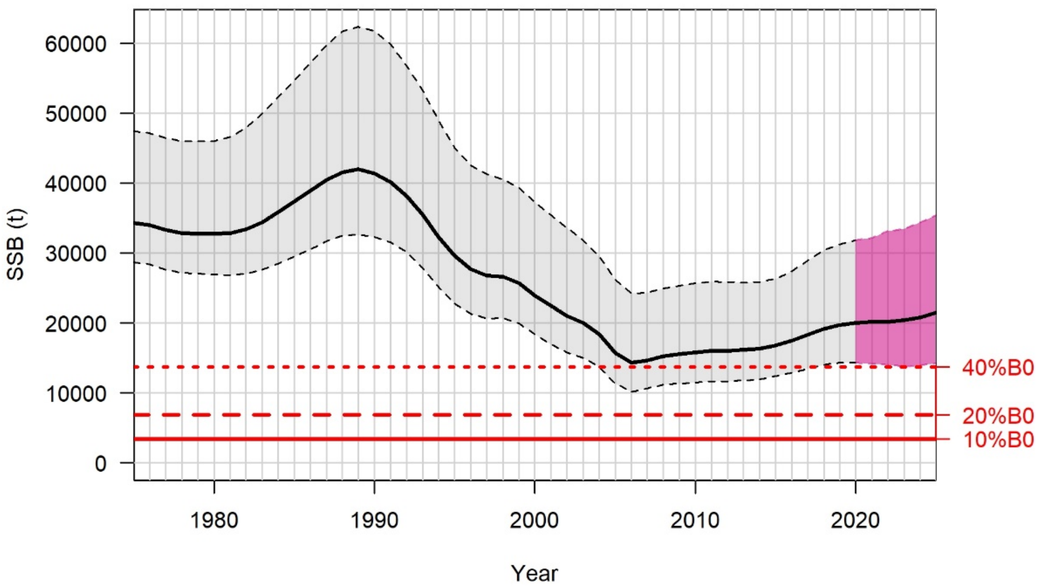

Figure C23: Projection using MCMC. 'CPUE east' run using all estimated year class strengths to estimate future year class strengths. Future catch option: Average last 6 years.

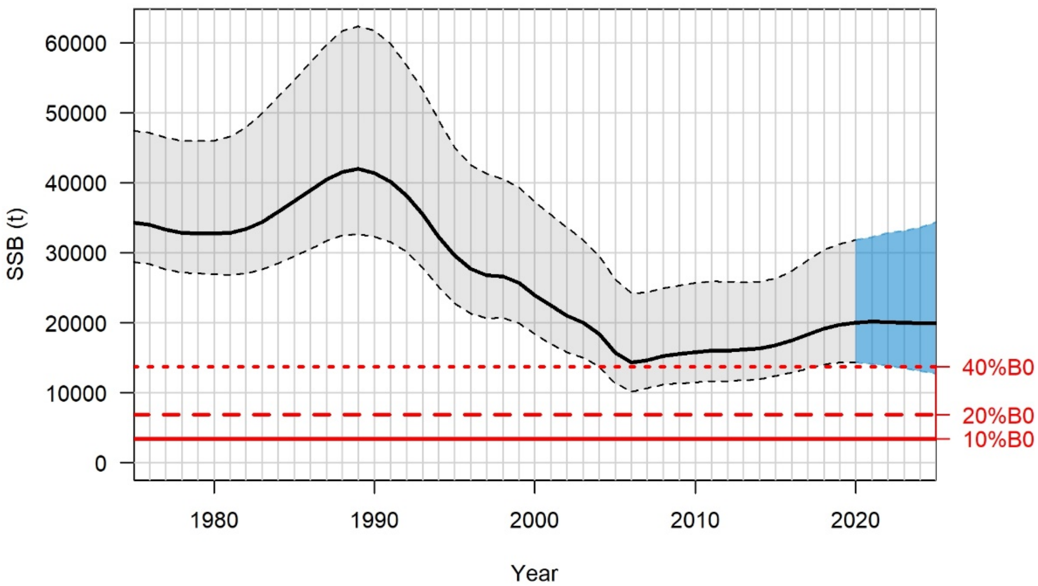

Figure C24: Projection using MCMC. 'CPUE-east' run using most recent 10 estimated year class strengths to estimate future year class strengths. Future catch option: Average last 6 years.

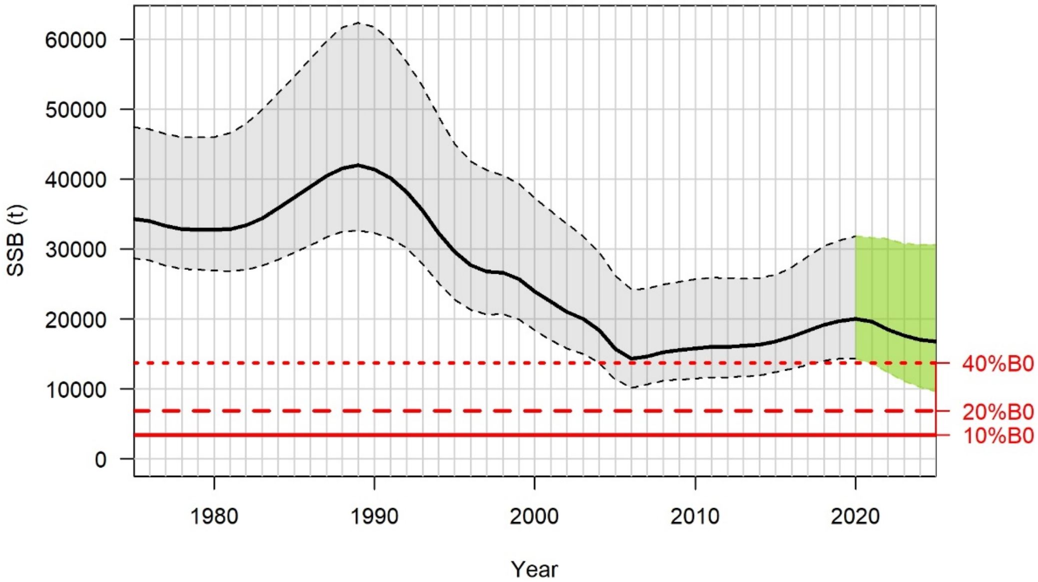

Figure C25: Projection using MCMC. 'CPUE-east' run using all estimated year class strengths to estimate future year class strengths. Future catch option: TACC.

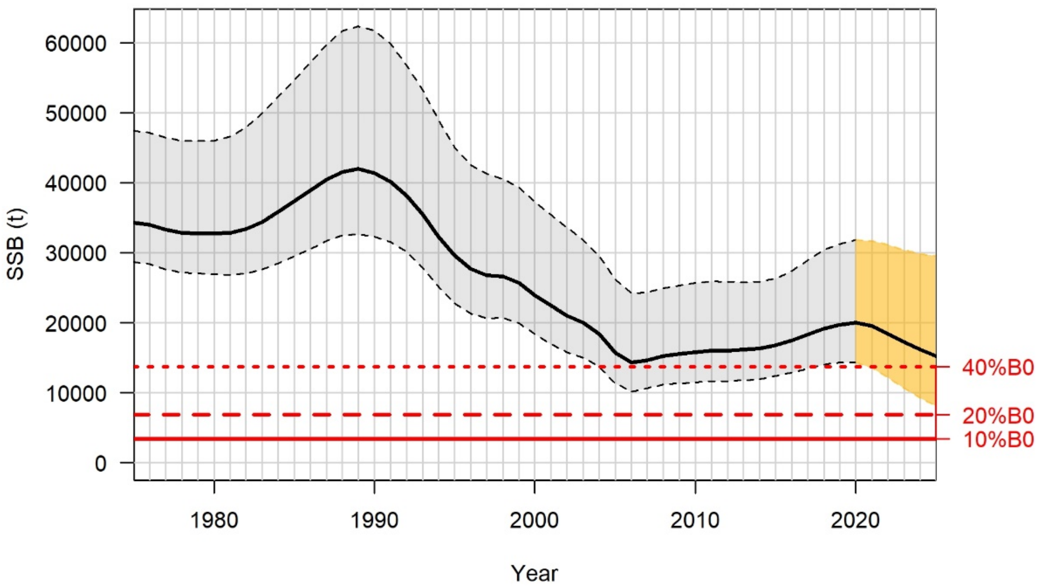

Figure C26: Projection using MCMC. 'CPUE-east' run using most recent 10 estimated year class strengths to estimate future year class strengths. Future catch option: TACC.