



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

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P.L. Horn

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EXECUTIVE SUMMARY

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.

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This report summarises the stock assessment for the 2016–17 fishing year of two stocks of hake, the WCSI stock (Quota Management Area HAK 7) and the Chatham Rise stock (HAK 4 and part of HAK 1). Updated Bayesian assessments were conducted using the general-purpose stock assessment program CASAL v2.30. The assessment incorporated all relevant biological parameters, the commercial catch histories, updated CPUE series, and series of proportion-at-age data from the commercial trawl fisheries and research surveys. The analysis includes fishery data up to the end of the 2015–16 fishing year.

The stock assessment of hake on the Chatham Rise has been updated using a model without sex in the partition, with biomass fitting primarily to the summer research survey series. Stock assessments have produced consistent estimates of the hake Chatham Rise stock status. The stock was steadily fished down throughout the 1990s, but spawning biomass (B_{2016}) was estimated to still be 48% of B_0 . Strong year classes spawned in 2002 and 2011 (in contrast to generally poor spawning success in other years from 1995 to 2013) resulted in a stock rebuild. An annual catch equal to the HAK 4 TACC (1800 t) over the next five years will probably maintain the stock at its current level. A lower catch level will allow further increase in biomass. The stock is probably being well monitored by the January trawl survey series, which showed evidence of a uniform decline in biomass from 1992 to about 2005. Sensitivity analyses incorporating a CPUE series as a further biomass index gave a slightly more optimistic estimate of stock status (B_{2016} was 55% of B_0), as did a model run where instantaneous natural mortality was estimated (B_{2016} was 58% of B_0).

The stock assessment of hake off west coast South Island has been updated using a model without sex in the partition, with biomass fitting either to a trawl fishery CPUE series from 2001 to 2011 (CPUE model), or to the four comparable trawl survey indices from 2000 to 2016 (survey model). Both models indicated that the stock was steadily fished down for 20 years from about 1990. The survey model indicated that the spawning stock was currently at about 26% B_0 , and that continued fishing at recent catch levels is likely to allow stock size to increase slowly, but only if some future recruited year classes are stronger than the average since 2000. Increases in catches or continued poor recruitment will probably cause further stock declines. In contrast to the model run using the trawl survey biomass index, the CPUE model run indicated that current stock status was much higher, at about 50% B_0 , and that at current or increased landings levels the stock biomass in 2012 had a low probability (i.e., less than a 6% chance) of being lower than 20% B_0 , even if future recruitment remains as poor as it has been since about 2000. Clearly, there is a need to try to determine which of the two relative abundance indices is most accurate, and therefore, which of the two assessment scenarios should be given primacy in the management of west coast hake.

1. INTRODUCTION

This report outlines the stock assessment of hake (*Merluccius australis*) stocks on the West Coast South Island (WCSI; Quota Management Area (QMA) HAK 7) and on the Chatham Rise (HAK 4 and part of HAK 1) with the inclusion of data up to the end of the 2015–16 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 on 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 assessments of hake off WCSI and Chatham Rise are presented as Bayesian assessments implemented as single stock models 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 DEE201609 “To update the stock assessment of hake, including biomass estimates and sustainable yields”, funded by the Ministry for Primary Industries. Revised catch histories for all three hake stocks are reported here, as are any new model input data and research results. Although some of these data are not relevant to the assessment reported here, they are included to provide in one place an up-to-date summary of the available knowledge and literature on hake in New Zealand waters.

1.1 Description of the fishery

Hake are widely distributed through 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, while 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 and southern blue whiting, 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 Quota Management Area (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 has been off the west coast of the South Island (HAK 7) with the highest catch (17 000 t) recorded in 1977, immediately before the establishment of the EEZ. In 2016–17, the TACC for HAK 7 is the largest, at 7700 t out of a total for the EEZ of 13 211 t (Ministry for Primary Industries 2017). The WCSI hake fishery has generally consisted of bycatch in the much larger hoki trawl fishery, but it has undergone a number of changes since about 2000 (Devine 2009, Ballara 2013). These include changes to the TACCs of both hake and hoki, and also changes in fishing practices such as gear used, tow duration, and strategies to limit hake bycatch. In some years, notably in 1992, 1993, 2006, and 2009 there has been a hake target fishery in September after the peak of the hoki fishery is over (Ballara 2013).

On the Chatham Rise and in the Sub-Antarctic, hake have been caught mainly as bycatch by trawlers targeting hoki, although significant targeting occurs in both areas (Ballara 2013, 2015). Increases in TACCs from 2610 t to 3500 t in HAK 1 and 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 these fish stocks. Reported catches rose over a number of years to the levels of the new TACCs in both HAK 1 and HAK 4, with catches in HAK 1 remaining relatively steady until about 2005. The TACC for HAK 1 has risen in several small jumps since then to its current level of 3701 t. Landings from HAK 4 steadily declined from 1998–99 to a low of 811 t in 2002–03, but increased to 2275 t in 2003–04. However, from 2004–05, the TACC

for HAK 4 was reduced from 3500 t to 1800 t with an overall TAC of 1818 t. Annual landings have been markedly lower than the new TACC since then. From 1 October 2005 the TACC for HAK 7 was increased to 7700 t with an overall TAC of 7777 t. This new catch limit was set equal to average annual catches over the previous 12 years, a catch level that was believed by the Working Group to be sustainable in the short term. Since the TACC increases, however, annual catch has approached 7700 t only once, and has been markedly lower in most other years.

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 2001–02 (Ballara 2013).

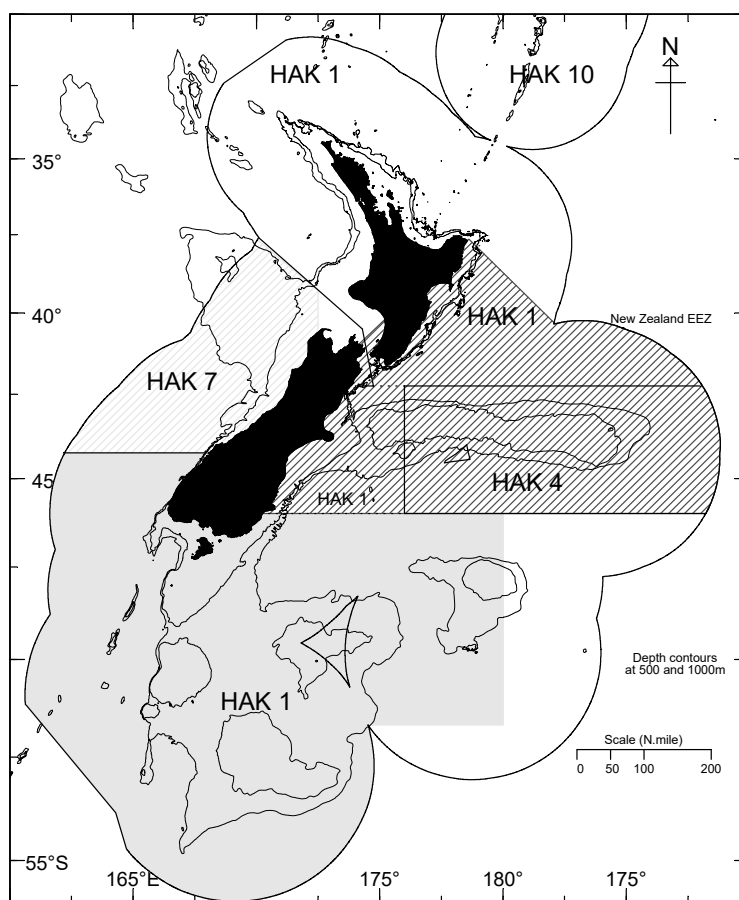


Figure 1: Quota Management Areas (QMAs) HAK 1, 4, 7, & 10; and the west coast South Island (light shading), Chatham Rise (dark shading), and Sub-Antarctic (medium shading) hake stock boundaries assumed in this report.

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), and 2012–13 (Horn 2013b). 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 2013b), Sub-Antarctic (Horn 2013a), and WCSI (Horn 2013b).

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 and 2016, 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 and 2016. 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 by Ballara (2013), and for the Sub-Antarctic stock 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).

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. REVIEW OF THE FISHERY

2.1 TACCs, catch, landings, and effort data

Reported catches from 1975 to 1987–88 are shown in Table 1, and reported landings for each QMA since 1983–84 and TACCs since 1986–87 are shown in Table 2. Revised estimates of landings by QMA for 1989–90 to 2010–11 (Table 3) were derived by examining the reported tow-by-tow catches of hake and correcting for possible misreporting, using the method of Dunn (2003a).

Revised landings by biological stock are given in Table 4. The derivation of the catch from 1974–75 to 1988–89 was described for the Chatham Rise and Sub-Antarctic stocks by Dunn et al. (2000) and for WCSI by Dunn (2004b). Landings since 1989–90 from Chatham Rise and Sub-Antarctic and since 1991–92 for WCSI were obtained from the corrected data used to produce Table 3, but this time summing the landings reported in each of the three shaded areas shown on Figure 1. WCSI revised estimates for 1988–89 to 1990–91 are from Colman & Vignaux (1992), who estimated the actual hake catch in HAK 7 by multiplying the total hoki catch (which was assumed to be correctly reported by vessels both with and without observers) by the ratio of hake to hoki in the catch of vessels carrying observers. Reported and estimated catches for 1988–89 were respectively 6835 t and 8696 t; for 1989–90, 4903 t reported and 8741 t estimated; and for 1990–91, 6189 t reported and 8246 t estimated.

Table 1: Reported hake catches (t) from 1975 to 1987–88. Data from 1975 to 1983 from Ministry of Agriculture & Fisheries (Fisheries); data from 1983–84 to 1985–86 from Fisheries Statistics Unit; data from 1986–87 to 1987–88 from Quota Management System (QMS).

Fishing year	New Zealand vessels			Foreign licensed vessels				Total
	Domestic	Chartered	Total	Japan	Korea	USSR	Total	
1975 ¹	0	0	0	382	0	0	382	382
1976 ¹	0	0	0	5 474	0	300	5 774	5 774
1977 ¹	0	0	0	12 482	5 784	1 200	19 466	19 466
1978–79 ²	0	3	3	398	308	585	1 291	1 294
1979–80 ²	0	5 283	5 283	293	0	134	427	5 710
1980–81 ²				No data available				
1981–82 ²	0	3 513	3 513	268	9	44	321	3 834
1982–83 ²	38	2 107	2 145	203	53	0	255	2 400
1983 ³	2	1 006	1 008	382	67	2	451	1 459
1983–84 ⁴	196	1 212	1 408	522	76	5	603	2 011
1984–85 ⁴	265	1 318	1 583	400	35	16	451	2 034
1985–86 ⁴	241	2 104	2 345	465	52	13	530	2 875
1986–87 ⁴	229	3 666	3 895	234	1	1	236	4 131
1987–88 ⁴	122	4 334	4 456	231	1	1	233	4 689

1. Calendar year; 2. 1 April to 31 March; 3. 1 April to 30 September; 4. 1 October to 30 September

Table 2: Reported landings (t) of hake by QMA from 1983–84 to 2010–11 and actual TACCs (t) for 1986–87 to 2015–16. Data from 1983–84 to 1985–86 from Fisheries Statistics Unit; data from 1986–87 to 2015–16 from Quota Management System (– indicates that the data are unavailable).

QMA	HAK 1		HAK 4		HAK 7		HAK 10		Total	
	Landings	TACC	Landings	TACC	Landings	TACC	Landings	TACC	Landings	TACC
1983–84	886	–	180	–	945	–	0	–	2 011	–
1984–85	670	–	399	–	965	–	0	–	2 034	–
1985–86	1 047	–	133	–	1 695	–	0	–	2 875	–
1986–87	1 022	2 500	200	1 000	2 909	3 000	0	10	4 131	6 510
1987–88	1 381	2 500	288	1 000	3 019	3 000	0	10	4 689	6 510
1988–89	1 487	2 513	554	1 000	6 835	3 004	0	10	8 876	6 527
1989–90	2 115	2 610	763	1 000	4 903	3 310	0	10	7 783	6 930
1990–91	2 603	2 610	743	1 000	6 148	3 310	0	10	9 567	6 930
1991–92	3 156	3 500	2 013	3 500	3 026	6 770	0	10	8 196	13 780
1992–93	3 525	3 501	2 546	3 500	7 154	6 835	0	10	13 224	13 846
1993–94	1 803	3 501	2 587	3 500	2 974	6 835	0	10	7 363	13 847
1994–95	2 572	3 632	3 369	3 500	8 841	6 855	0	10	14 781	13 997
1995–96	3 956	3 632	3 465	3 500	8 678	6 855	0	10	16 082	13 997
1996–97	3 534	3 632	3 524	3 500	6 118	6 855	0	10	13 176	13 997
1997–98	3 809	3 632	3 523	3 500	7 416	6 855	0	10	14 749	13 997
1998–99	3 845	3 632	3 324	3 500	8 165	6 855	0	10	15 333	13 997
1999–00	3 899	3 632	2 803	3 500	6 898	6 855	0	10	13 600	13 997
2000–01	3 504	3 632	2 472	3 500	8 134	6 855	0	10	14 110	13 997
2001–02	2 870	3 701	1 424	3 500	7 519	6 855	0	10	11 813	14 066
2002–03	3 336	3 701	811	3 500	7 433	6 855	0	10	11 581	14 066
2003–04	3 461	3 701	2 272	3 500	7 943	6 855	0	10	13 686	14 066
2004–05	4 797	3 701	1 266	1 800	7 316	6 855	0	10	13 377	12 366
2005–06	2 743	3 701	305	1 800	6 906	7 700	0	10	9 955	13 211
2006–07	2 025	3 701	900	1 800	7 668	7 700	0	10	10 592	13 211
2007–08	2 445	3 701	865	1 800	2 620	7 700	0	10	5 930	13 211
2008–09	3 415	3 701	856	1 800	5 954	7 700	0	10	10 226	13 211
2009–10	2 156	3 701	208	1 800	2 351	7 700	0	10	4 715	13 211
2010–11	1 904	3 701	179	1 800	3 754	7 700	0	10	5 838	13 211

Table 2 ctd.

QMA	HAK 1		HAK 4		HAK 7		HAK 10		Total	
	Landings	TACC	Landings	TACC	Landings	TACC	Landings	TACC	Landings	TACC
2011–12	1 948	3 701	161	1 800	4 459	7 700	0	10	6 568	13 211
2012–13	2 079	3 701	177	1 800	5 434	7 700	0	10	7 690	13 211
2013–14	1 883	3 701	168	1 800	3 642	7 700	0	10	5 693	13 211
2014–15	1 725	3 701	304	1 800	6 219	7 700	0	10	8 248	13 211
2015–16	1 584	3 701	274	1 800	2 864	7 700	0	10	4 722	13 211

Table 3: Revised reported landings (t) by QMA 1989–90 to 2014–15 (from Ballara 2017).

Fishing Year	QMA			Total
	HAK 1	HAK 4	HAK 7	
1989–90	2 115	763	4 903	7 781
1990–91	2 592	726	6 175	9 494
1991–92	3 141	2 007	3 048	8 196
1992–93	3 522	2 546	7 157	13 225
1993–94	1 787	2 587	2 990	7 364
1994–95	2 263	2 855	9 659	14 780
1995–96	3 805	3 028	9 153	15 987
1996–97	3 285	2 865	6 950	13 100
1997–98	3 659	3 237	7 686	14 581
1998–99	3 702	2 882	8 929	15 513
1999–00	3 747	2 447	7 086	13 280
2000–01	3 429	2 321	8 351	14 101
2001–02	2 865	1 420	7 499	11 784
2002–03	3 334	805	7 406	11 545
2003–04	3 455	2 254	7 943	13 652
2004–05	4 795	1 260	7 302	13 357
2005–06	2 742	305	6 897	9 944
2006–07	2 006	900	7 660	10 566
2007–08	2 442	865	2 615	5 922
2008–09	3 409	854	5 945	10 208
2009–10	2 156	208	2 340	4 704
2010–11	1 904	179	3 716	5 799
2011–12	1 948	161	4 428	6 537
2012–13	2 056	177	5 426	7 659
2013–14	1 883	168	3 620	5 671
2014–15	1 721	280	6 195	8 196

Table 4: Estimated landings (t) from fishing years 1974–75 to 2014–15 for the Sub-Antarctic (Sub-A), Chatham Rise (Chat), and west coast South Island (WCSI) biological stocks (areas as defined in Figure 1).

Fishing yr	Sub-A	Chat	WCSI	Fishing yr	Sub-A	Chat	WCSI
1974–75	120	191	71	1995–96	2 873	4 028	9 082
1975–76	281	488	5 005	1996–97	2 262	4 234	6 838
1976–77	372	1 288	17 806	1997–98	2 606	4 252	7 674
1977–78	762	34	498	1998–99	2 796	3 669	8 742
1978–79	364	609	4 737	1999–00	3 020	3 517	7 031
1979–80	350	750	3 600	2000–01	2 790	2 962	8 346
1980–81	272	997	2 565	2001–02	2 510	1 770	7 498
1981–82	179	596	1 625	2002–03	2 738	1 401	7 404
1982–83	448	302	745	2003–04	3 245	2 465	7 939
1983–84	722	344	945	2004–05	2 531	3 526	7 298
1984–85	525	544	965	2005–06	2 557	489	6 892
1985–86	818	362	1 918	2006–07	1 818	1 081	7 660
1986–87	713	509	3 755	2007–08	2 202	1 096	2 583
1987–88	1 095	574	3 009	2008–09	2 427	1 825	5 912
1988–89	1 237	804	8 696	2009–10	1 958	391	2 282
1989–90	1 927	950	8 741	2010–11	1 288	951	3 462
1990–91	2 370	931	8 246	2011–12	1 892	194	4 299
1991–92	2 750	2 418	3 001	2012–13	1 863	344	5 171
1992–93	3 269	2 798	7 059	2013–14	1 830	187	3 387
1993–94	1 453	2 934	2 971	2014–15	1 630	348	5 966
1994–95	1 852	3 387	9 535				

2.2 Recreational and Maori customary fisheries

The recreational fishery for hake is believed to be negligible. The amount of hake caught by Maori is not known, but is believed to be negligible.

2.3 Other sources of fishing mortality

There is likely to be some mortality associated with escapement from trawl nets, but the level is not known and is assumed to be negligible.

3. BIOLOGY, STOCK STRUCTURE, AND ABUNDANCE INDICES

3.1 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). The best known area is off the west coast of the South Island, where the season can extend from June to October, possibly with a peak in September. Spawning also occurs to the west of the Chatham Islands during a prolonged period from at least September to January. Spawning fish have also been recorded occasionally near the Mernoo Bank on the western Chatham Rise. Spawning on the Campbell Plateau, primarily to the northeast of the Auckland Islands, may occur 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 (2017).

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, 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 (GSI, the ratio of the gonad weight to body weight). 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 $GSI \geq 0.005$ (males) or $GSI \geq 0.015$ (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 5, with ogives plotted in Figure 2; 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, Sub-Antarctic hake at about 6 years for males and 6.5 years for females, and WCSI hake at about 4.5 years for males and 5 years for females.

Von Bertalanffy growth model parameters were previously estimated using data up to 1997 (Horn 1998). The parameters for all three stocks were updated using all data available at February 2007 (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 5). 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 on both sides 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 $0.20\text{--}0.25 \text{ y}^{-1}$. 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). 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 assessments reported below estimated age-independent constant values of M within model sensitivity runs for the WCSI and Chatham Rise stocks.

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 were predominantly 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) using all available length-weight data collected during trawl surveys since 1989. Following a trawl survey off WCSI in July-August 2012, parameters for hake from that stock were also revised. Parameters were calculated for males, females, and both sexes combined (Table 5). Sample sizes were large (2165 males, 1828 females) and all r^2 values were greater than 0.97.

Table 5: Estimates of biological parameters for the three hake stocks.

		Estimate		Source									
<i>Natural mortality</i>													
	Males	$M = 0.20$		(Dunn et al. 2000)									
	Females	$M = 0.18$		(Dunn et al. 2000)									
	Both sexes	$M = 0.19$											
<i>Weight = $a(\text{length})^b$ (Weight in t, length in cm)</i>													
Sub-Antarctic	Males	$a = 2.13 \times 10^{-9}$	$b = 3.281$	(Horn 2013a)									
	Females	$a = 1.83 \times 10^{-9}$	$b = 3.314$	(Horn 2013a)									
	Both sexes	$a = 1.95 \times 10^{-9}$	$b = 3.301$	(Horn 2013a)									
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)									
WCSI	Males	$a = 2.85 \times 10^{-9}$	$b = 3.209$	(Horn 2013b)									
	Females	$a = 1.94 \times 10^{-9}$	$b = 3.307$	(Horn 2013b)									
	Both sexes	$a = 2.01 \times 10^{-9}$	$b = 3.294$	(Horn 2013b)									
<i>von Bertalanffy growth parameters</i>													
Sub-Antarctic	Males	$k = 0.295$	$t_0 = 0.06$	$L_\infty = 88.8$	(Horn 2008)								
	Females	$k = 0.220$	$t_0 = 0.01$	$L_\infty = 107.3$	(Horn 2008)								
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)								
WCSI	Males	$k = 0.357$	$t_0 = 0.11$	$L_\infty = 82.3$	(Horn 2008)								
	Females	$k = 0.280$	$t_0 = 0.08$	$L_\infty = 99.6$	(Horn 2008)								
<i>Schnute growth parameters ($\tau_1 = 1$ and $\tau_2 = 20$ for all stocks)</i>													
Sub-Antarctic	Males	$y_1 = 22.3$	$y_2 = 89.8$	$a = 0.249$	$b = 1.243$	(Horn 2008)							
	Females	$y_1 = 22.9$	$y_2 = 109.9$	$a = 0.147$	$b = 1.457$	(Horn 2008)							
	Both sexes	$y_1 = 22.8$	$y_2 = 101.8$	$a = 0.179$	$b = 1.350$	(Horn 2013a)							
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)							
WCSI	Males	$y_1 = 23.7$	$y_2 = 83.9$	$a = 0.278$	$b = 1.380$	(Horn 2008)							
	Females	$y_1 = 24.5$	$y_2 = 103.6$	$a = 0.182$	$b = 1.510$	(Horn 2008)							
	Both sexes	$y_1 = 24.5$	$y_2 = 98.5$	$a = 0.214$	$b = 1.570$	(Horn 2011)							
<i>Maturity ogives (proportion mature at age)</i>													
	Age	2	3	4	5	6	7	8	9	10	11	12	13
SubAnt	Males	0.01	0.04	0.11	0.30	0.59	0.83	0.94	0.98	0.99	1.00	1.00	1.00
	Females	0.01	0.03	0.08	0.19	0.38	0.62	0.81	0.92	0.97	0.99	1.00	1.00
	Both	0.01	0.03	0.09	0.24	0.49	0.73	0.88	0.95	0.98	0.99	1.00	1.00
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
WCSI	Males	0.01	0.05	0.27	0.73	0.95	0.99	1.00	1.00	1.00	1.00	1.00	1.00
	Females	0.02	0.07	0.25	0.57	0.84	0.96	0.99	1.00	1.00	1.00	1.00	1.00
	Both	0.01	0.06	0.26	0.65	0.90	0.97	0.99	1.00	1.00	1.00	1.00	1.00
<i>Miscellaneous parameters</i>													
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								

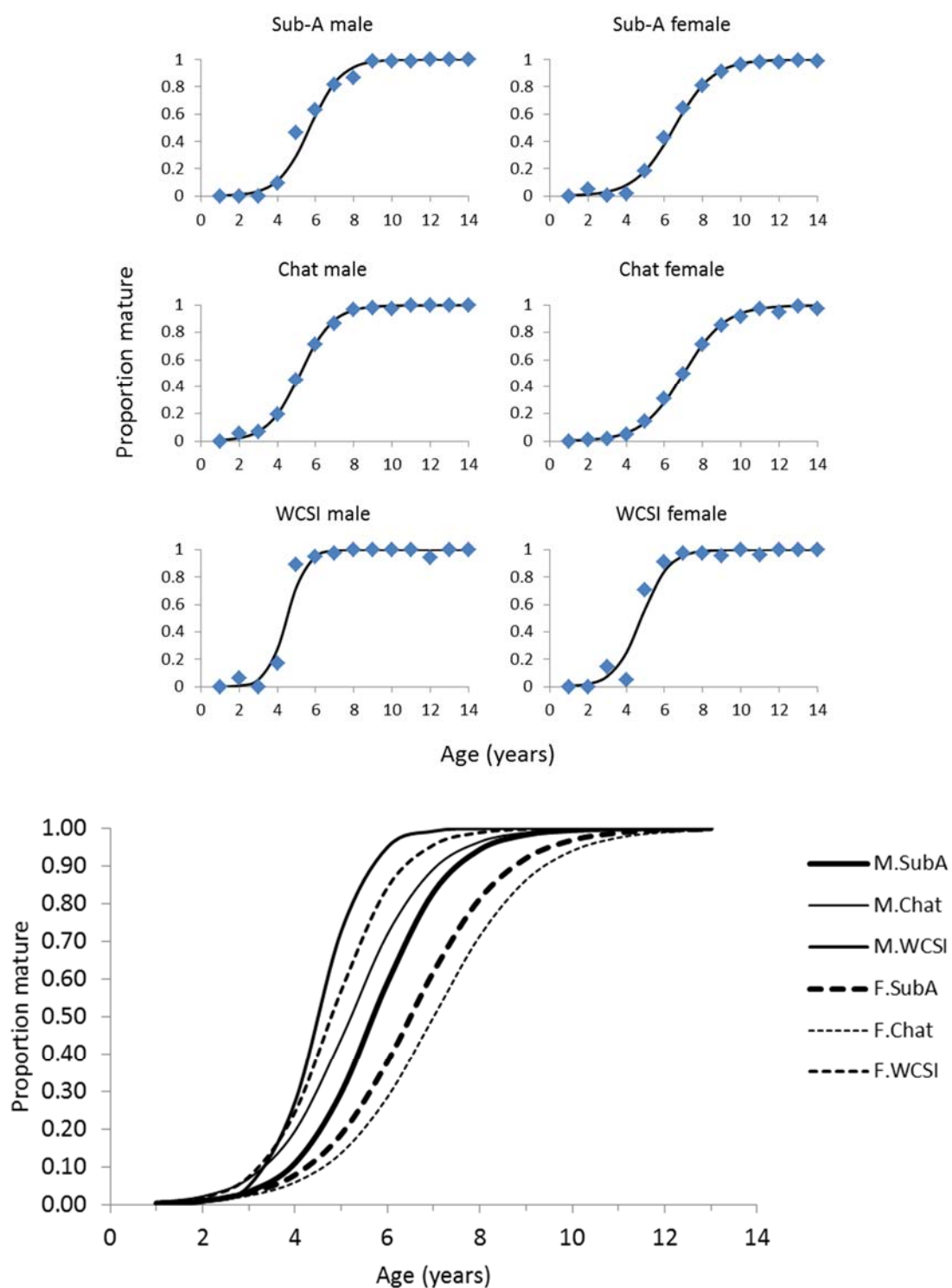


Figure 2: Raw proportion mature at age data with fitted logistic ogives (upper panel), and a comparison plot (lower panel) of all estimated ogives by stock for male (M, solid lines) and female (F, broken lines) hake.

3.2 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 on the west coast. The Puysegur fish were most similar to 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). The Sub-Antarctic stock was considered to contain hake in the remaining Puysegur, Southland, and Sub-Antarctic regions of the HAK 1 management area. The stock areas assumed for this report are shown earlier, in Figure 1.

3.3 Resource surveys

In the Sub-Antarctic, three resource surveys were carried out by *Tangaroa* with the same gear and similar survey designs in November–December 1991, 1992, and 1993, but the series was then terminated as there was evidence that hake, in particular, might be aggregated for spawning at that time of the year and that spawning aggregations had a high probability of being missed during a survey. However, research interest in hoki in the Sub-Antarctic resulted in a return to the November–December survey annually in 2000–2009, 2011, 2012, 2014 and 2016. Surveys by *Tangaroa* in April 1992, May 1993, April 1996, and April 1998 formed the basis for a second series, with hake appearing to be more evenly distributed through the survey area at that time of year. A single survey in September 1992 by *Tangaroa* was also completed. The biomass estimates from the Sub-Antarctic *Tangaroa* and 1989 *Amaltal Explorer* surveys are shown in Table 6 with further details given in Appendix A.

Sub-Antarctic surveys were conducted by *Shinkai Maru* (March–May 1982 and October–November 1983) and *Amaltal Explorer* (October–November 1989, July–August 1990, and November–December 1990). However, these vessels used different gear and had different performance characteristics (Livingston et al. 2002), so cannot be used as part of a consistent time series.

The resource surveys carried out at depths of 200–800 m on the Chatham Rise annually from 1992 to 2014 and in 2016 by *Tangaroa* had the same gear and similar survey designs (see Appendix A). While 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 deepwater 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, as in the Sub-Antarctic, 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 7 with further details in Appendix A. Catch distributions from these surveys are plotted by Stevens et al. (2011).

Table 6: Research survey indices (and associated CVs) for the Sub-Antarctic stock. The Nov–Dec series is based on indices from 300–800 m core strata, including the 800–1000 m strata in Puysegur, but excluding Bounty Platform. The other series are based on the biomass indices from 300–800 m core strata, excluding the 800–1000 m strata in Puysegur and the Bounty Platform.

Fishing Year	Vessel	Nov–Dec series ¹		Apr–May series ²		Sep series ²	
		Biomass (t)	CV	Biomass (t)	CV	Biomass (t)	CV
1989	<i>Amaltal</i>	2 660	0.21				
1992	<i>Tangaroa</i>	5 686	0.43	5 028	0.15	3 760	0.15
1993	<i>Tangaroa</i>	1 944	0.12	3 221	0.14		
1994	<i>Tangaroa</i>	2 567	0.12				
1996	<i>Tangaroa</i>			2 026	0.12		
1998	<i>Tangaroa</i>			2 554	0.18		
2001	<i>Tangaroa</i>	2 657	0.16				
2002	<i>Tangaroa</i>	2 170	0.20				
2003	<i>Tangaroa</i>	1 777	0.16				
2004	<i>Tangaroa</i>	1 672	0.23				
2005	<i>Tangaroa</i>	1 694	0.21				
2006	<i>Tangaroa</i>	1 459	0.17				
2007	<i>Tangaroa</i>	1 530	0.17				
2008	<i>Tangaroa</i>	2 470	0.15				
2009	<i>Tangaroa</i>	2 162	0.17				
2010	<i>Tangaroa</i>	1 442	0.20				
2012	<i>Tangaroa</i>	2 004	0.23				
2013	<i>Tangaroa</i>	1 943	0.25				
2015	<i>Tangaroa</i>	1 477	0.25				
2017	<i>Tangaroa</i>	1 000	0.25				

Research surveys of hoki and hake have been conducted periodically off WCSI, but these have generally been ‘one-off’ surveys by different vessels (i.e., *Shinkai Maru* in 1976, *James Cook* in 1978–79, *Wesermünde* in 1979, and *Giljanes* in 1990) so any biomass estimates from them are not useful model inputs. However, a combined trawl and acoustic survey by *Tangaroa* in 2000 (O’Driscoll et al. 2004) was replicated (with some modifications) in the winters of 2012, 2013 and 2016 (O’Driscoll & Ballara 2017), so a four year comparable time series is available (Table 7). The biomass estimates from the four surveys were standardised using random day-time bottom trawl stations in strata 12A, B, and C, and 4A, B, and C, with stratum areas from the 2012 survey (O’Driscoll & Ballara 2017). A long-running trawl survey series of inshore waters off WCSI by *Kaharoa* has not provided a useful index of hake biomass as it surveys no deeper than 400 m (Stevenson & Hanchet 2000). Age data, and consequent estimates of proportion-at-age, are available for the four comparable *Tangaroa* surveys. Proportion-at-age data are also available from the 1979 *Wesermünde* survey; these data are included in the assessment model with the WCSI commercial trawl fishery data set as the selectivity ogive for this vessel is likely to be more similar to the commercial fleet than to the *Tangaroa* survey gear (N. Bagley, NIWA, pers. comm.).

Table 7: Research survey indices (and associated CVs) for the Chatham Rise and WCSI stocks. The indices relate to the core survey strata only, i.e. 200–800 m for Chatham Rise and 300–650 m for WCSI.

Year	Vessel	Chatham Rise		WCSI		
		Biomass (t)	CV	Vessel	Biomass (t)	CV
1989	<i>Amaltal Explorer</i>	3 576	0.19			
1992	<i>Tangaroa</i>	4 180	0.15			
1993	<i>Tangaroa</i>	2 950	0.17			
1994	<i>Tangaroa</i>	3 353	0.10			
1995	<i>Tangaroa</i>	3 303	0.23			
1996	<i>Tangaroa</i>	2 457	0.13			
1997	<i>Tangaroa</i>	2 811	0.17			
1998	<i>Tangaroa</i>	2 873	0.18			
1999	<i>Tangaroa</i>	2 302	0.12			
2000	<i>Tangaroa</i>	2 090	0.09	<i>Tangaroa</i>	803	0.13
2001	<i>Tangaroa</i>	1 589	0.13			
2002	<i>Tangaroa</i>	1 567	0.15			
2003	<i>Tangaroa</i>	890	0.16			
2004	<i>Tangaroa</i>	1 547	0.17			
2005	<i>Tangaroa</i>	1 049	0.18			
2006	<i>Tangaroa</i>	1 384	0.19			
2007	<i>Tangaroa</i>	1 820	0.12			
2008	<i>Tangaroa</i>	1 257	0.13			
2009	<i>Tangaroa</i>	2 419	0.21			
2010	<i>Tangaroa</i>	1 700	0.25			
2011	<i>Tangaroa</i>	1 099	0.15			
2012	<i>Tangaroa</i>	1 292	0.15	<i>Tangaroa</i>	583	0.13
2013	<i>Tangaroa</i>	1 877	0.15	<i>Tangaroa</i>	331	0.17
2014	<i>Tangaroa</i>	1 377	0.15			
2015	No survey	—				
2016	<i>Tangaroa</i>	1 299	0.14	<i>Tangaroa</i>	221	0.24

3.4 Observer age samples

3.4.1 Chatham Rise

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 3. Mean fish length tends to increase from west to east, and with increasing depth. 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 (2017)) were from almost all years between 1991–92 and 2015–16. 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 3), 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.

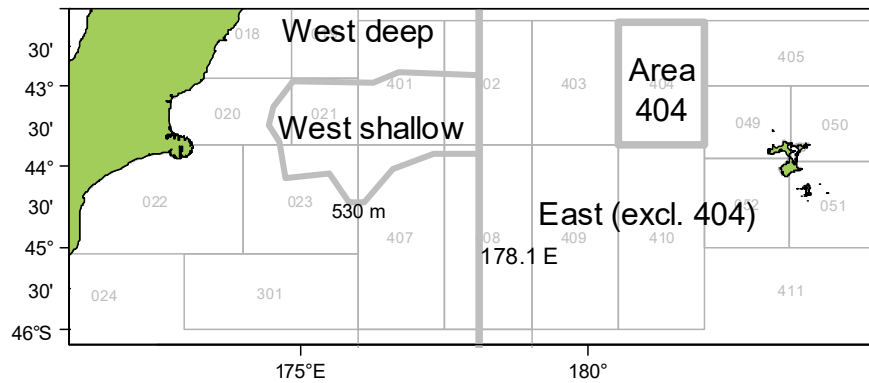


Figure 3: Fishery strata defined for the Chatham Rise hake fishery. Large numbers show longitudes or depths of fishery boundaries; small numbers denote statistical areas. The stratum boundary defined by depth (530 m) is shown only approximately. Isobaths at 1000, 500, and 250 m are also shown.

3.4.2 Sub-Antarctic

The Sub-Antarctic hake observer data were found to be best stratified into the four areas shown in Figure 4 (Horn 2008). Most of the hake target fishing, and most of the catch (average 94% per year), is associated with the Snares-Pukaki area. Puysegur is the next most important area with about 3% of the catch. Available observer data are also concentrated in the Snares-Pukaki region, but it is clear that the smaller fisheries (particularly the Campbell Island area) have been over-sampled in most years. Consequently, the Sub-Antarctic observer data were analysed as one major and three very minor fisheries, having a single common fishery selectivity ogive. However, because of clear differences in mean fish length between the fisheries (Horn 2008), it is important to use the four fishery strata when calculating catch-at-age distributions. Without stratification, the frequent over-sampling in the minor fisheries could strongly bias the catch-at-age distributions. Because the annual landing of hake from outside the Snares-Pukaki area are very low relative to the Snares-Pukaki catch it is considered to be satisfactory to apply a single age-length key to the scaled length-frequency distributions for each fishery to produce the catch-at-age data. Catch-at-age distributions from the Sub-Antarctic trawl fishery are available from all but three years from 1989–90 to 2015–16 (Horn & Sutton 2017).

3.4.3 WCSI

The fishery off WCSI 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). A single catch-at-age distribution was estimated for each year, stratified as shown in Figure 4, with the otoliths used to construct the age-length key being sampled from across the entire fishery (areally and temporally). Catch-at-age distributions from the WCSI trawl fishery are available from 1978–79 and all years from 1989–90 to 2015–16 (Horn & Sutton 2017).

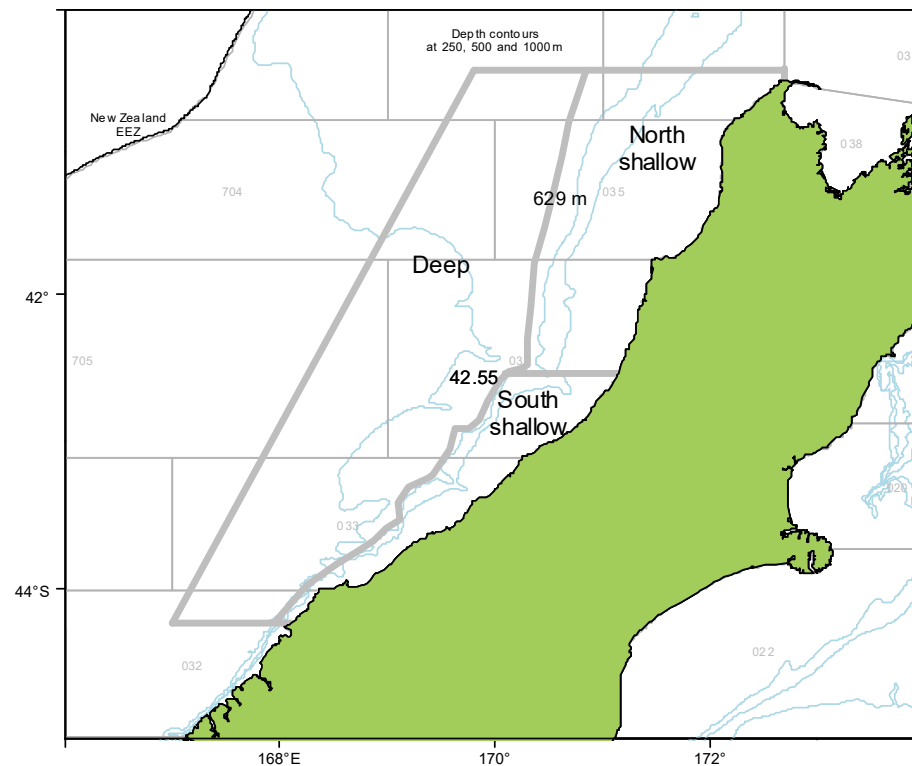
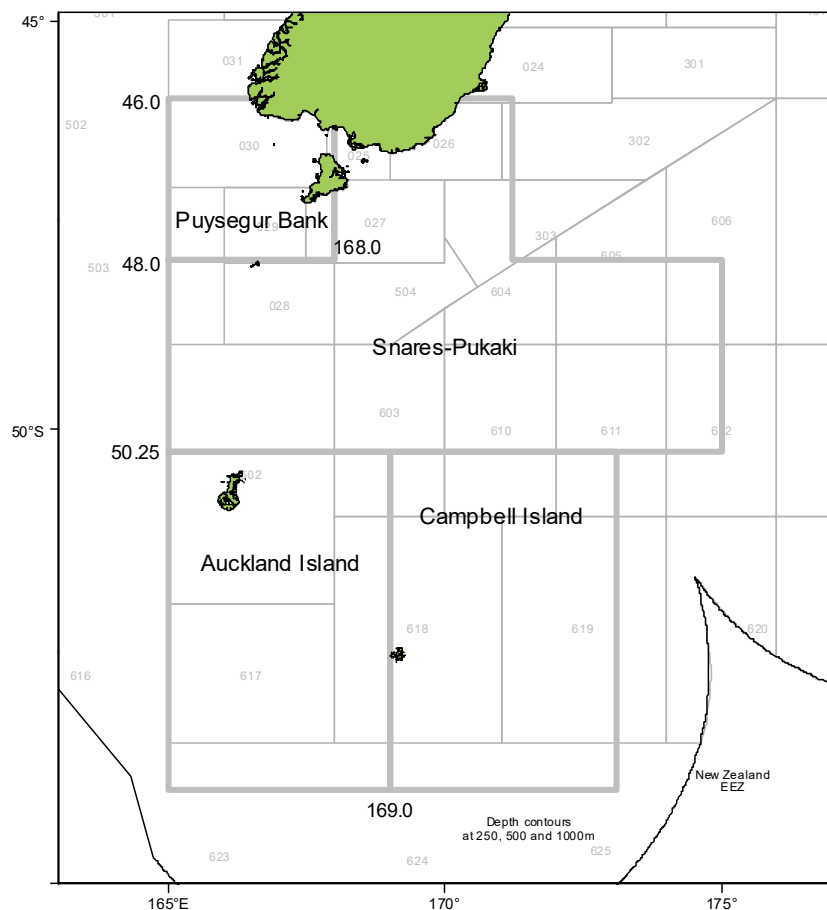


Figure 4: Fishery strata defined for the Sub-Antarctic (left panel) and WCSI (right panel) hake fisheries. Large numbers show latitudes, longitudes, or depths of fishery boundaries; small numbers denote statistical areas. The WCSI stratum boundary defined by depth (629 m) is shown only approximately. Isobaths at 1000, 500, and 250 m are also shown.

3.5 CPUE indices

As the Chatham Rise and WCSI hake assessments were being completed under the current project, standardised CPUE series from these areas were updated, using data to the end of the 2014–15 fishing year (Ballara 2017). CPUE series were produced for the eastern fishery on the Chatham Rise using QMS data, and for the WCSI winter fishery using observer data (Table 8). These were the series chosen by the Deepwater Working Group for inclusion in previous assessments (Horn 2013a, 2013b). For the Chatham Rise, the series analysing the daily processed catch from the eastern fishery was selected; the western fishery series were rejected because there were unexplained differences between the daily processed and tow-by-tow indices. For the WCSI, the series analysing observer estimated tow-by-tow data since 2001 was selected. It was believed that this series, incorporating catch data after the establishment of the deemed value system, was the least likely to be biased by changes in fishing behaviour and catch reporting behaviour (Ballara 2013). In these CPUE series, each annual index relates to a fishing year (i.e., October to September).

Table 8: Hake CPUE indices (and associated CVs) used in assessments of the Chatham Rise and WCSI hake stocks (from Ballara 2017).

Year	Chatham east		WCSI observer	
	Index	CV	Index	CV
1989–90	2.21	0.15	—	—
1990–91	1.77	0.09	—	—
1991–92	1.10	0.07	—	—
1992–93	1.27	0.06	—	—
1993–94	1.41	0.06	—	—
1994–95	1.00	0.04	—	—
1995–96	1.34	0.06	—	—
1996–97	1.24	0.05	—	—
1997–98	0.99	0.04	—	—
1998–99	0.90	0.03	—	—
1999–00	1.23	0.04	—	—
2000–01	1.08	0.04	0.95	0.04
2001–02	0.95	0.04	2.13	0.04
2002–03	0.73	0.04	0.94	0.07
2003–04	0.83	0.04	0.98	0.04
2004–05	0.51	0.04	0.80	0.04
2005–06	0.53	0.05	1.00	0.04
2006–07	0.83	0.05	0.71	0.06
2007–08	0.87	0.05	0.44	0.05
2008–09	0.95	0.05	0.36	0.06
2009–10	0.77	0.06	0.72	0.06
2010–11	0.62	0.05	1.18	0.05
2011–12	0.52	0.05	1.24	0.04
2012–13	0.66	0.06	1.35	0.03
2013–14	0.79	0.05	1.03	0.03
2014–15	0.89	0.05	1.15	0.03

4. MODEL STRUCTURE, INPUTS, AND ESTIMATION

Updated assessments of the Chatham Rise and west coast South Island (WCSI) stocks are presented here. As in the most recent previous assessments of these stocks (Horn & Francis 2010, Horn 2011, 2013b) the assessment models 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 9). 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). For WCSI, the model’s annual cycle was based on a year beginning on 1 November and divided into two steps (Table 9). The fishing year is not used in this assessment because landings peaks tend to occur from June to October, so it is logical to include the October catch with landings from the four months immediately preceding it, rather than with catches taken about eight months later. 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 9: Annual cycle of the Chatham Rise and WCSI stock models, 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, and spawning	0.42	0.25	January trawl survey	100
2	Mar–May	None	0.25	0.50		
3	Jun–Aug	Increment age	0.33	0.00		
WCSI						
1	Nov–May	Recruitment	0.42	0.50	Proportions-at-age Winter trawl survey	50
2	Jun–Oct	Fishing, spawning and increment age	0.58	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.

For all models discussed below, assumed values of fixed biological parameters are given in Table 5. 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 as 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 reached.

Biomass estimates from the resource surveys were used as relative biomass indices, with associated CVs estimated from the survey analysis (Table 7). 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, from commercial observer data for the fishery, and (for WCSI) from the research voyage by *Wesermünde* in 1979. The error distributions assumed were multinomial for the proportions-at-age and proportions-at-length data, and lognormal for all other data. An additional process error CV

of 0.2 was added to the WCSI trawl survey biomass index following Francis et al. (2001). A process error CV of 0.2 was initially applied to the Chatham Rise trawl survey biomass index for the MPD model runs, but was estimated in an MPD run to be 0.15, and this value was applied in all MCMC runs. Process error CVs for the CPUE series were estimated following Francis (2011); values of 0.2 and 0.3 were applied to the Chatham Rise and WCSI series, respectively. The multinomial observation error effective sample sizes for the at-age data were adjusted using the reweighting procedure of Francis (2011); effective and adjusted sample sizes for each of the age distributions are listed in Table 10. 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 10: Initial sample sizes (*N*_{init}) and adjusted sample sizes (*N*_{adj}) for each of the fishery and trawl survey age distributions used in the Chatham Rise and WCSI assessments. *N*_{adj} is the effective sample size assumed in all model final runs. ‘Factor’ is the value used to determine *N*_{adj} from *N*_{init}.

Year	Chatham Rise						WCSI			
	Fishery west		Fishery east		Trawl survey		Fishery		Trawl survey	
	<i>N</i> _{init}	<i>N</i> _{adj}	<i>N</i> _{init}	<i>N</i> _{adj}	<i>N</i> _{init}	<i>N</i> _{adj}	<i>N</i> _{init}	<i>N</i> _{adj}	<i>N</i> _{init}	<i>N</i> _{adj}
1979							385	16		
1990					125	25	286	12		
1991							474	20		
1992	392	27	92	19	187	37	287	12		
1993					155	31	212	9		
1994	130	9			168	34	186	8		
1995	166	11	87	18	109	22	245	10		
1996	167	11			100	20	359	15		
1997	95	7	73	15	103	21	326	14		
1998	797	55	109	23	94	19	349	15		
1999	441	30			86	17	637	27		
2000	449	31			157	31	440	18	279	31
2001	465	32	255	53	114	23	319	13		
2002	331	23			119	24	358	15		
2003	209	14			52	10	439	18		
2004	224	15	208	43	81	16	416	17		
2005	247	17			82	16	276	12		
2006	115	8			99	20	479	20		
2007			201	42	107	21	508	21		
2008	277	19			83	17	509	21		
2009	169	12			136	27	398	17		
2010	174	12			82	16	218	9		
2011	136	9			66	13	491	21		
2012					64	13	739	31	231	26
2013					68	14	753	32	157	18
2014	163	12			48	10	784	33		
2015			141	29			780	33		
2016	232	16			83	17	728	31	52	6
Factor		0.069		0.210		0.200		0.041		0.111

Year class strengths were assumed known (and equal to one) for years before 1975 and after 2013 (Chatham Rise), and before 1973 and after 2009 (WCSI), 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 2015–16 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 2016 were produced. At the same time, catch histories for FMA 3 and FMA 4 were also produced. For each year from 1990 to 2016, the proportions of the FMA 3 catch made up by the ‘west shallow’ and ‘west deep’ fisheries were calculated, as were the proportions of the FMA 4 landings made up by the ‘east’ fishery. Means over all years indicated that the ‘west shallow’ and ‘west deep’ fisheries accounted for landings of 99% and 75% respectively of the FMA 3 total, and that the ‘east’ fishery took landings equivalent to 83% of the FMA 4 total. [Note that the percentages for ‘west’ and ‘east’ do not equate to 100% because the western fisheries include an area greater than FMA 3, and the eastern fishery comprises an area smaller than FMA 4.] Dunn et al. (2006) had produced estimates of total Chatham Rise hake catch from 1975 to 1989, and the FMA 4 catch from 1984 to 1989. Estimates of FMA 4 catch before 1984 were obtained primarily from Colman & Livingston (1988). Hence, estimates of hake catch from FMA 3 and FMA 4 from 1975 to 1989 were available or could be derived. To estimate catch by fishery from 1975 to 1989, the percentages presented above were applied to the FMA 3 or FMA 4 landings. Catch histories by fishery are presented in Table 11.

For the WCSI stock, the catch history assumed in all model runs is as estimated for the WCSI section of HAK 7 by fishing year up to 1990–91, and by the year commencing 1 November from 1991–92 (Table 12).

Table 11: Estimated catch (t) by FMA (3 and 4) from the Chatham Rise stock, and total catch, by fishing year, and estimated catch (t) by fishery for the model years. Note that from 1989–90 totals by fishing year and model year differ because the September catch has been shifted from the fishing year into the following model year. Landings from the most recent year are estimated assuming catch patterns similar to the previous year.

Fishing year	FMA 3	FMA 4	Total	Model year	West	East	Total
1974–75	50	141	191	1975	80	111	191
1975–76	88	400	488	1976	152	336	488
1976–77	37	1 251	1 288	1977	74	1 214	1 288
1977–78	24	10	34	1978	28	6	34
1978–79	55	554	609	1979	103	506	609
1979–80	350	400	750	1980	481	269	750
1980–81	840	157	997	1981	914	83	997
1981–82	290	306	596	1982	393	203	596
1982–83	102	200	302	1983	154	148	302
1983–84	164	180	344	1984	224	120	344
1984–85	145	399	544	1985	232	312	544
1985–86	229	133	362	1986	282	80	362
1986–87	309	200	509	1987	387	122	509
1987–88	286	288	574	1988	385	189	574
1988–89	250	554	804	1989	386	418	804
1989–90	196	763	959	1990	309	689	998
1990–91	207	698	905	1991	409	503	912
1991–92	402	2 012	2 414	1992	718	1 087	1 805
1992–93	266	2 542	2 808	1993	656	1 996	2 652
1993–94	350	2 583	2 933	1994	368	2 912	3 280
1994–95	452	2 934	3 386	1995	597	2 903	3 500
1995–96	875	3 038	3 913	1996	1 353	2 483	3 836
1996–97	924	2 737	3 661	1997	1 475	1 820	3 295
1997–98	1 000	2 983	3 983	1998	1 424	1 124	2 547
1998–99	831	2 541	3 372	1999	1 169	3 339	4 509
1999–00	640	2 302	2 942	2000	1 155	2 130	3 285
2000–01	435	2 069	2 504	2001	1 208	1 700	2 908
2001–02	355	1 414	1 769	2002	454	1 058	1 512
2002–03	602	812	1 414	2003	497	718	1 215
2003–04	210	2 281	2 491	2004	687	1 983	2 671
2004–05	2 485	1 268	3 753	2005	2 585	1 434	4 019
2005–06	54	305	359	2006	184	255	440
2006–07	181	900	1 081	2007	270	683	953
2007–08	233	865	1 098	2008	259	901	1 159
2008–09	971	854	1 825	2009	1 069	832	1 902
2009–10	183	208	391	2010	231	159	390
2010–11	772	179	951	2011	822	118	940
2011–12	60	161	221	2012	70	154	224
2012–13	154	177	331	2013	215	164	379
2013–14	44	168	212	2014	65	150	215
2014–15	79	304	383	2015	62	174	236
2015–16	–	–	–	2016	110	230	340

Table 12: Reported catch (t) from FMA 7 and estimated catch from the WCSI biological stock (area as defined in Figure 1), by fishing year, and estimated catch (t) for the model years. Note that from 1991–92 totals by fishing year and model year often differ because the October catch has been shifted from the fishing year into the previous model year. The catch from the most recent year is estimated assuming catch patterns similar to recent previous years.

Fishing year	FMA 7	WCSI	Model year	WCSI
1974–75	71	71	1975	71
1975–76	5 005	5 005	1976	5 005
1976–77	17 806	17 806	1977	17 806
1977–78	498	498	1978	498
1978–79	4 737	4 737	1979	4 737
1979–80	3 600	3 600	1980	3 600
1980–81	2 565	2 565	1981	2 565
1981–82	1 625	1 625	1982	1 625
1982–83	745	745	1983	745
1983–84	945	945	1984	945
1984–85	965	965	1985	965
1985–86	1 918	1 918	1986	1 918
1986–87	3 755	3 755	1987	3 755
1987–88	3 009	3 009	1988	3 009
1988–89	8 696	8 696	1989	8 696
1989–90	4 903	8 741	1990	8 741
1990–91	6 175	8 246	1991	8 246
1991–92	3 048	3 001	1992	3 004
1992–93	7 157	7 059	1993	7 056
1993–94	2 990	2 971	1994	2 987
1994–95	9 659	9 535	1995	9 604
1995–96	9 153	9 082	1996	9 053
1996–97	6 950	6 838	1997	6 877
1997–98	7 686	7 674	1998	7 674
1998–99	8 929	8 742	1999	8 842
1999–00	7 086	7 031	2000	6 907
2000–01	8 351	8 346	2001	8 277
2001–02	7 519	7 498	2002	7 590
2002–03	7 433	7 404	2003	7 590
2003–04	7 945	7 939	2004	7 915
2004–05	7 317	7 298	2005	7 336
2005–06	6 905	6 892	2006	6 659
2006–07	7 668	7 660	2007	7 664
2007–08	2 620	2 583	2008	2 557
2008–09	5 954	5 912	2009	5 946
2009–10	2 352	2 282	2010	2 451
2010–11	3 754	3 463	2011	3 428
2011–12	4 459	4 297	2012	4 402
2012–13	5 434	5 170	2013	5 422
2013–14	3 642	3 387	2014	3 628
2014–15	6 219	5 966	2015	6 187
2015–16	—	—	2016	4 900

4.1 Prior distributions and penalty functions

The assumed prior distributions used in the Chatham Rise and WCSI assessments are given in Table 13. 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 by assuming that the catchability constant was the product of areal availability, vertical availability, and vulnerability. This same q prior was used in the previous Chatham Rise hake assessment (Horn 2013b). A simple simulation was conducted that 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 fishery and trawl survey selectivity parameters were assumed to be uniform, except in a sensitivity run 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 very tight distribution set for age at full selectivity (a_1 , see Figure 10; Table 13), but an essentially uniform distribution for parameters a_L and a_R . The values of survey catchability constants are dependent on the selectivity parameters, and the absolute catchability can be determined by the product of the selectivity by age and sex, and the catchability constant q . M was estimated in a sensitivity run, and was assumed to have a normal distribution with a mean at 0.19 (i.e., the constant value assumed in other models). The prior of 0.19 was estimated outside the model (Dunn et al. 2000).

Table 13: The assumed 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
	YCS	Lognormal	1.0	1.1	0.01	100
	Selectivity (fishery & survey)	Uniform	–	–	1	25–200*
	Selectivity (survey, a_1) [#]	Normal-by-stdev	8	1	1	25
	Selectivity (survey, a_L , a_R) [#]	Normal-by-stdev	10	500	1	50–200*
	M	Normal	0.19	0.2	0.1	0.35
WCSI	B_0	Uniform-log	–	–	5 000	250 000
	YCS	Lognormal	1.0	1.1	0.01	100
	Survey q	Lognormal	0.09	0.79	0.01	0.25
	Selectivity	Uniform	–	–	1	25–200*
	M	Normal	0.19	0.2	0.1	0.35

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

[#] The informed prior on the Chatham Rise survey a_1 parameter was used in a single sensitivity model run.

For the WCSI assessment, priors for all selectivity parameters were assumed to be uniform. The prior for the WCSI survey q was informative and was estimated using the Chatham Rise hake survey priors as a starting point because the survey series in both areas used the same vessel and fishing gear. However, the WCSI survey area in the 200–800 m depth range in strata 0004 A–C and 0012 A–C comprised 12 928 km² (O’Driscoll & Ballara 2017); seabed area in that depth range in the entire HAK 7 biological stock area (excluding the Challenger Plateau) is estimated to be about 24 000 km². So because biomass from only 54% of the WCSI hake habitat was included in the indices, the Chatham Rise prior on μ was modified accordingly (i.e., $0.16 \times 0.54 = 0.09$), and the bounds were also reduced from [0.01, 0.40] to [0.01, 0.25]. In a sensitivity run where M was estimated, priors were the same as for the Chatham Rise model.

Penalty functions were used in the assessments of both stocks 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.

5. MODEL ESTIMATES FOR CHATHAM RISE HAKE

5.1 Developing a 'base' model

Some initial investigations were completed to develop a 'base' model. The initial structure of the model followed previous assessments, in which many sensitivity runs were completed and evaluated. The summer trawl survey series exhibited a relatively smooth trend over time, particularly in the earlier half of the series, and on this basis was probably a reasonable index of relative abundance. Consequently, in the model development stage it was assumed that any 'good' assessment model should fit the survey series well. Model parameters were estimated using Bayesian estimation implemented using the CASAL software. However, only the mode of the joint posterior distribution (MPD) was estimated in these initial runs. Full details of the CASAL algorithms, software, and methods were detailed by Bull et al. (2012).

An initial model (model 1) was set up, with the partition excluding sex and maturity. 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 over all years in the fisheries and the survey series. All selectivity ogives were estimated using the double-normal parameterisation. A constant value of 0.19 was used for M . No CPUE series was incorporated. In this initial model run, the survey biomass was reasonably well fitted (Figure 5).

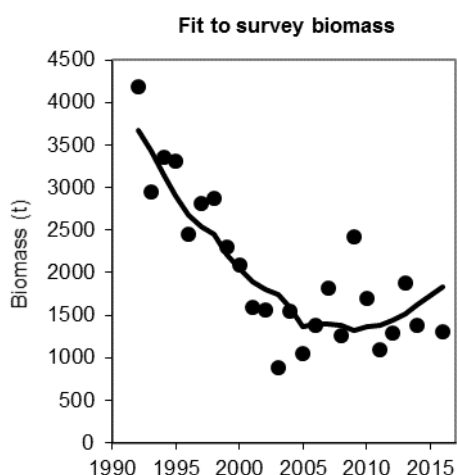


Figure 5: Fits to the research survey biomass, from model 1.

It was apparent, however, that the estimated selectivity ogive for the research survey was not satisfactory in model run 1. Age at full selectivity was estimated to be about 14 years (Figure 6), yet most of the fish taken in the survey were aged 3–12 years. An examination of the survey age distributions indicated that age at full selectivity was likely to be around 8 years, and was almost certainly less than 10. Consequently, an additional model was tested (model 2) which was identical to model 1 except that it had a tight normal prior on age at full selectivity (a_1) strongly encouraging a value of 8 ± 2 years (Figure 7). In model 2, the estimated research selectivity ogive reached a peak at about 9 years (Figure 8). The MPD fits to the trawl survey age data were slightly degraded (an increase in the objective function of about 2.5 units), and the fit

to the survey biomass altered slightly (Figure 8) but resulted in little change to the total likelihood (+ 0.1). The overall objective function increased by 4.5. Despite the enforced difference in the survey selectivity ogive, there was little difference between models 1 and 2 in the fits obtained to the survey at-age data (Figure 9). The fits obtained in model 2 to the western and eastern fishery at-age data are shown in Figures 10 and 11.

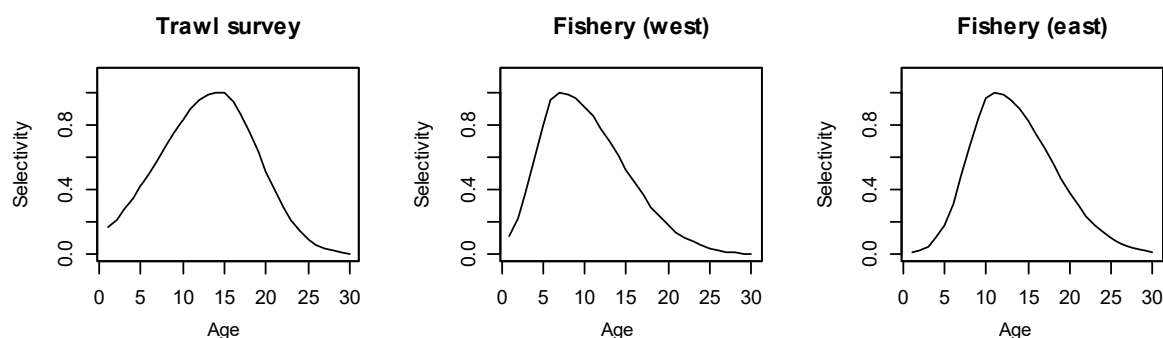


Figure 6: Estimated selectivity ogives for the research survey and two commercial fisheries from model 1.

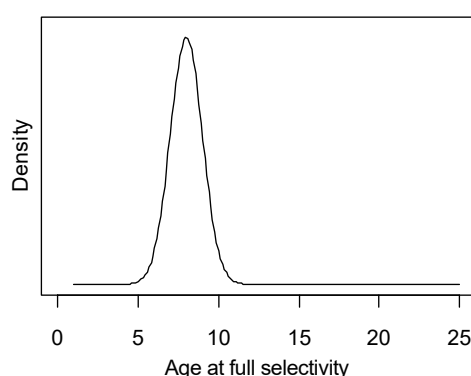


Figure 7: Distribution of the prior on age at full selectivity (a1) for the research survey selectivity ogive used in model 2.

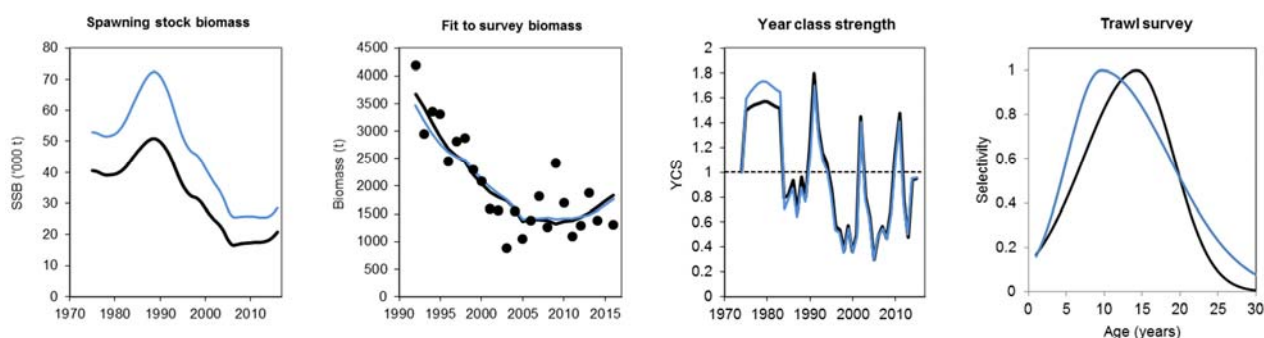


Figure 8: Biomass trajectory, fits to the trawl survey biomass index, estimated year class strengths, and estimated selectivity ogives for the research survey, from model 1 (black lines) and model 2 (blue lines).

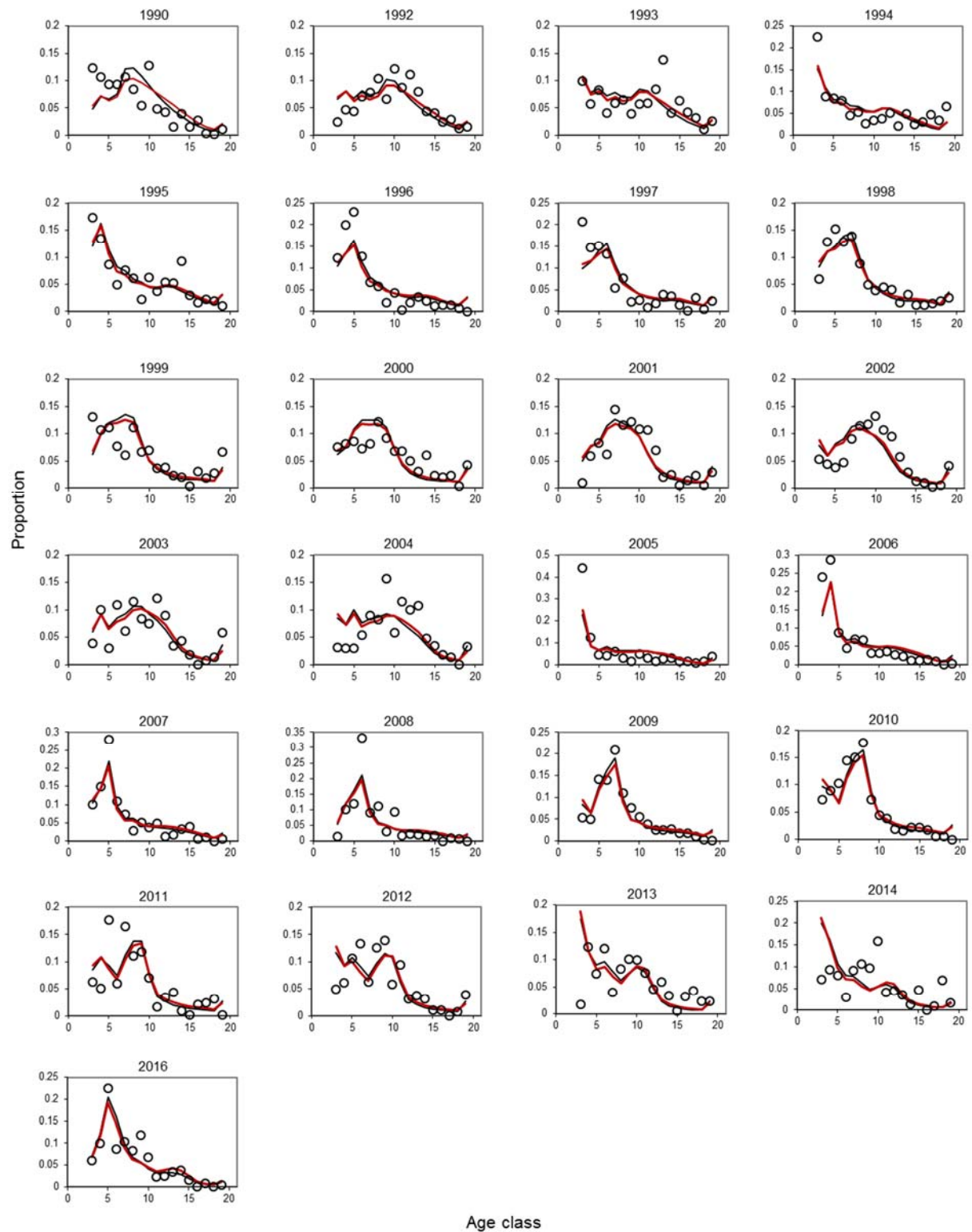


Figure 9: Fits from model 2 (black lines) and model 1 (red lines) to the trawl survey proportion-at-age distributions (circles).

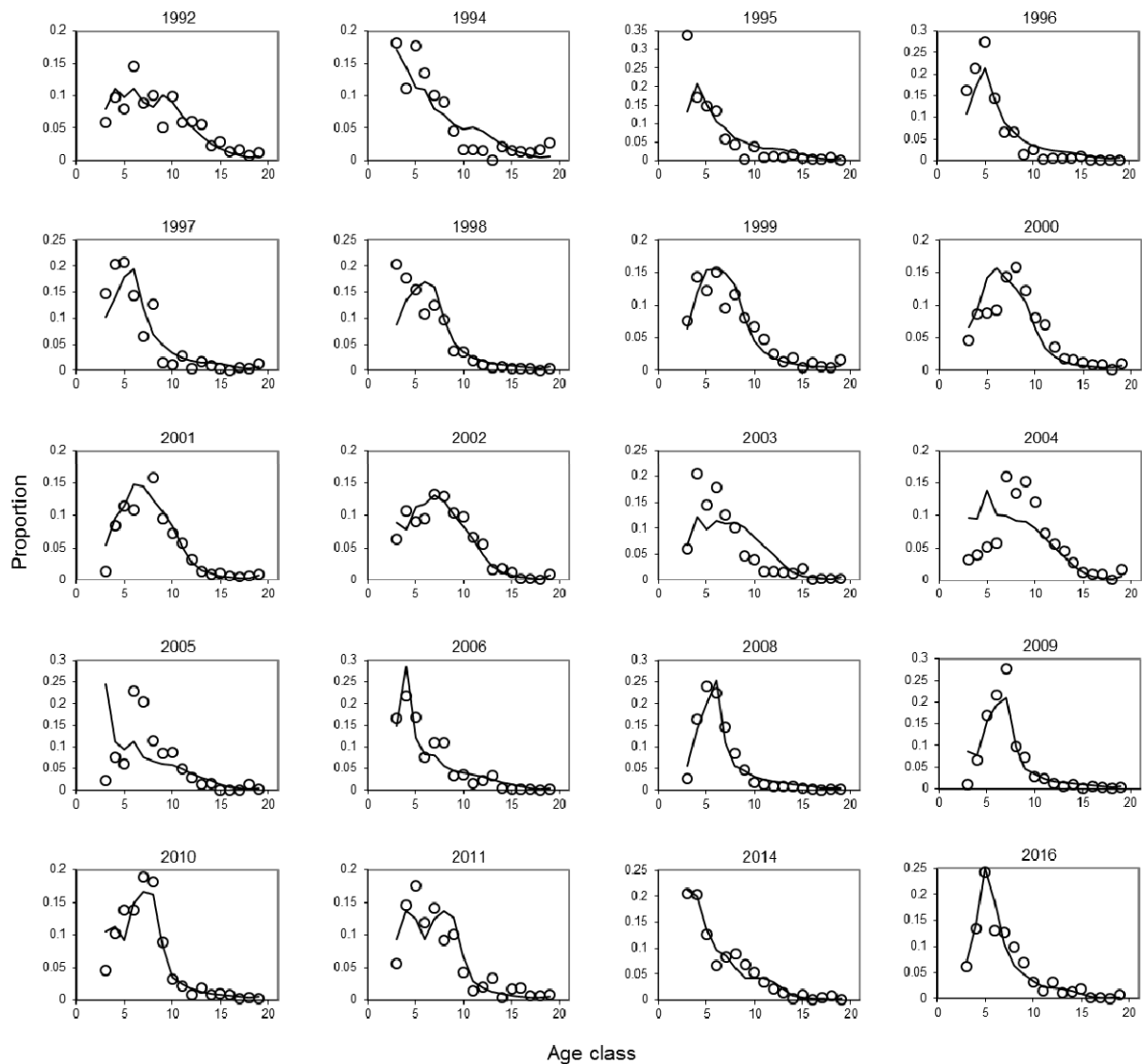


Figure 10: Fits (lines) to the western trawl fishery proportion-at-age distributions (circles), from model 2.

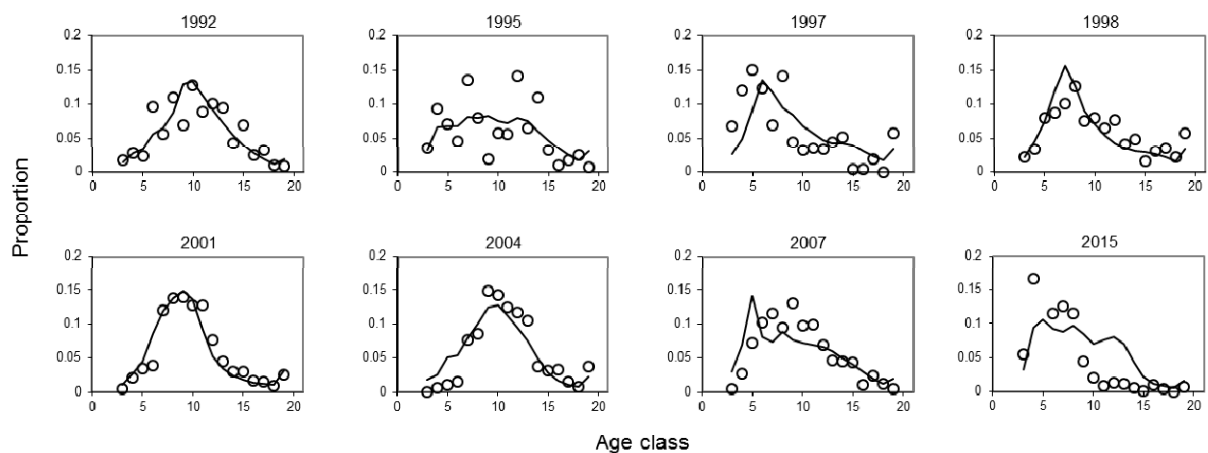


Figure 11: Fits (lines) to the eastern trawl fishery proportion-at-age distributions (circles), from model 2.

Three additional MPD models examined variations to model 2; estimation of an age-varying M , inclusion of the CPUE series, and including sex in the partition. Model 3 was the same as model 2 except that M was

estimated as a double-exponential ogive, and the selectivity ogive for the eastern fishery was fitted as a logistic curve. Relative to model 2, the resulting fit to the survey biomass series was virtually identical, the biomass trajectory was lower in absolute terms, and there was a slight improvement in the total objective function (a reduction of 2.5 units) (Figure 12). The estimated M ogive was considered plausible (Figure 12).

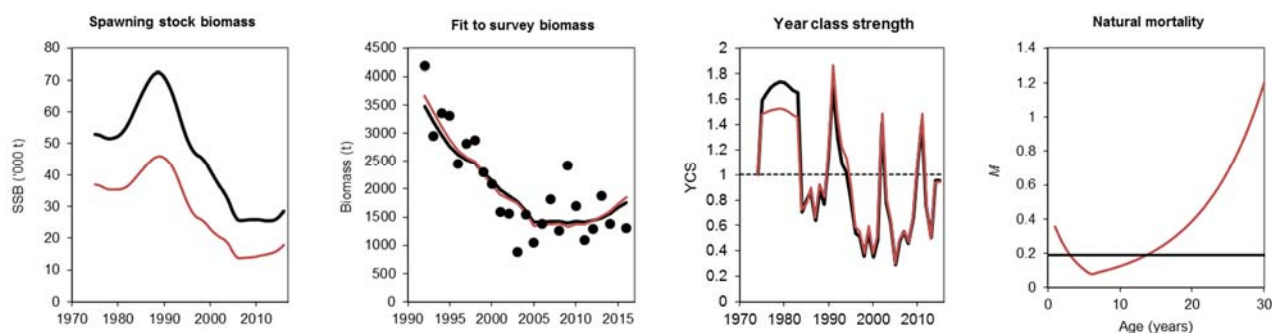


Figure 12: Biomass trajectory, fits to the trawl survey biomass index, estimated year class strengths, and estimated natural mortality ogive, from model 2 (black lines) and model 3 (red lines).

Model 4 examined the usefulness of the chosen CPUE series by including it in model 2. The fit to the CPUE was good, but inclusion of this data set did result in a slightly worse fit to the trawl biomass series (i.e., an increase in the objective function of about 1) (Figure 13). It also resulted in an elevation of the biomass trajectory (Figure 13). Clearly, the signal from the CPUE did not strongly conflict with the signal from the research survey series.

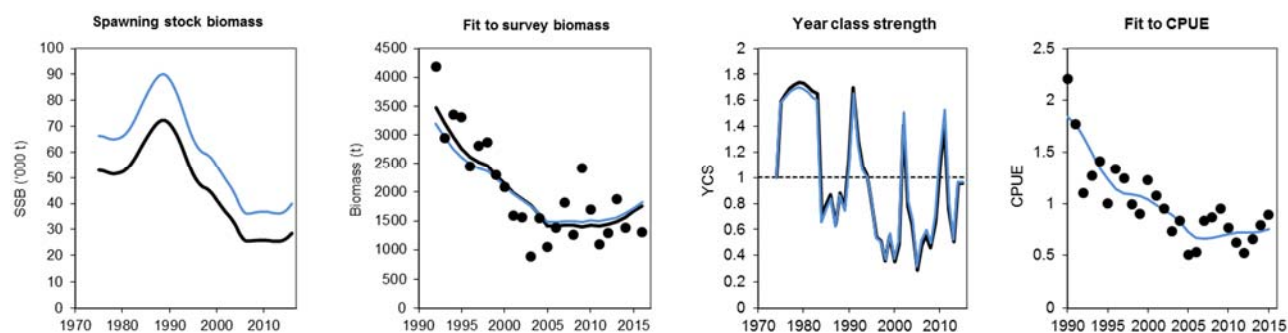


Figure 13: Biomass trajectory, fits to the trawl survey biomass index, estimated year class strengths, and fits to the CPUE series, from model 2 (black lines) and model 4 (blue lines).

A likelihood profile for model 4 (the model which includes all the available data sets) showed that none of the data series clearly defined the level of B_0 (Figure 14). The east age and survey age, and CPUE, provided information only on the lower bound to B_0 . The west age and survey biomass provided information only on the upper bound to B_0 . The relative weighting of these two groups of data therefore determines the shape of the total likelihood, and the B_0 estimate. It also implies some conflict between these data sets, e.g., between the east and west ages. The only component providing information on both upper and lower bounds to B_0 was the effect of the penalties and priors.

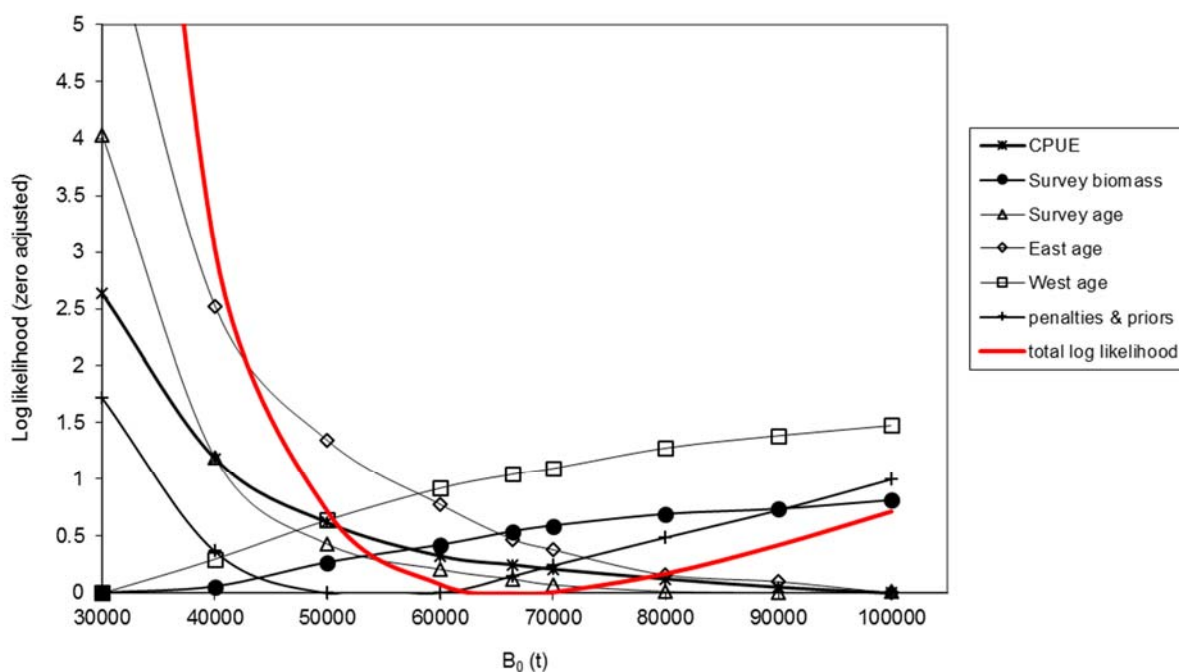


Figure 14: Likelihood profile (smoothed lines) on B_0 for model 4, showing both the total likelihood (red line) and those for individual data series.

Model 5 included sex in the partition, had sexed catch-at-age data, and had separate growth curves for males and females. It produced only very slight lowering of the biomass trajectory, and negligible changes to the trawl survey biomass fit and the estimated year class strengths (Figure 15). The selectivity ogives were not markedly different between sexes, particularly for the trawl survey and the western fishery (Figure 16). The ogive for female hake in the eastern fishery, however, lacks plausibility.

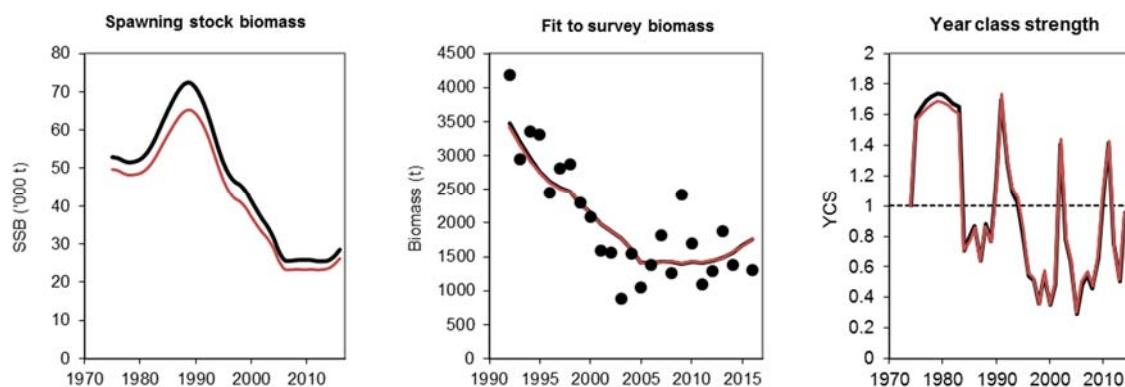


Figure 15: Biomass trajectory, fits to the trawl survey biomass index, and estimated year class strengths, from model 2 (black lines) and model 5 (red lines).



Figure 16: Estimated selectivity ogives (solid lines for males, broken lines for females) for the research survey and two commercial fisheries from model 5.

Following the evaluation of the MPD fits to the numerous sensitivity runs above, the Deepwater Fisheries Working Group concluded that the best base case model for MCMC estimation was model 2 ('Tight survey prior'). Three sensitivity variations to the base case were fully investigated. They were:

- Model 1, with the unconstrained trawl survey ogive ('Free survey ogive'),
- The 'free survey ogive' model but with M estimated as an age-independent constant ('Estimate M '), and;
- The 'free survey ogive' model with the inclusion of the CPUE series ('CPUE').

5.2 Model estimation using MCMC

Model parameters were estimated using Bayesian estimation implemented using the CASAL software. For final runs, the full posterior distribution was sampled using Monte Carlo Markov Chain (MCMC) methods, based on the Metropolis-Hastings algorithm. 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).

5.3 MCMC estimates

Estimates of the posterior distribution were obtained and are presented below. In addition, MCMC estimates of the median posterior and 95% percentile credible intervals are reported for the key output parameters. The MCMC chains for estimates of B_0 and B_{2016} from the 'tight survey prior' model (subsequently called the 'base case') appear moderately well converged (Figure 17). The distributions of estimates of B_0 and B_{2016} (as % B_0) from the base model were relatively consistent between the first, middle, and last thirds of the chain (Figure 17), and hence convergence was considered adequate for stock assessment purposes.

The MCMC estimates of B_0 (i.e., median around 33 000 t) are quite different to the MPD point estimate (i.e., 52 000 t, Figure 8). This is believed to occur when the MCMC posterior distribution is asymmetric and 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.

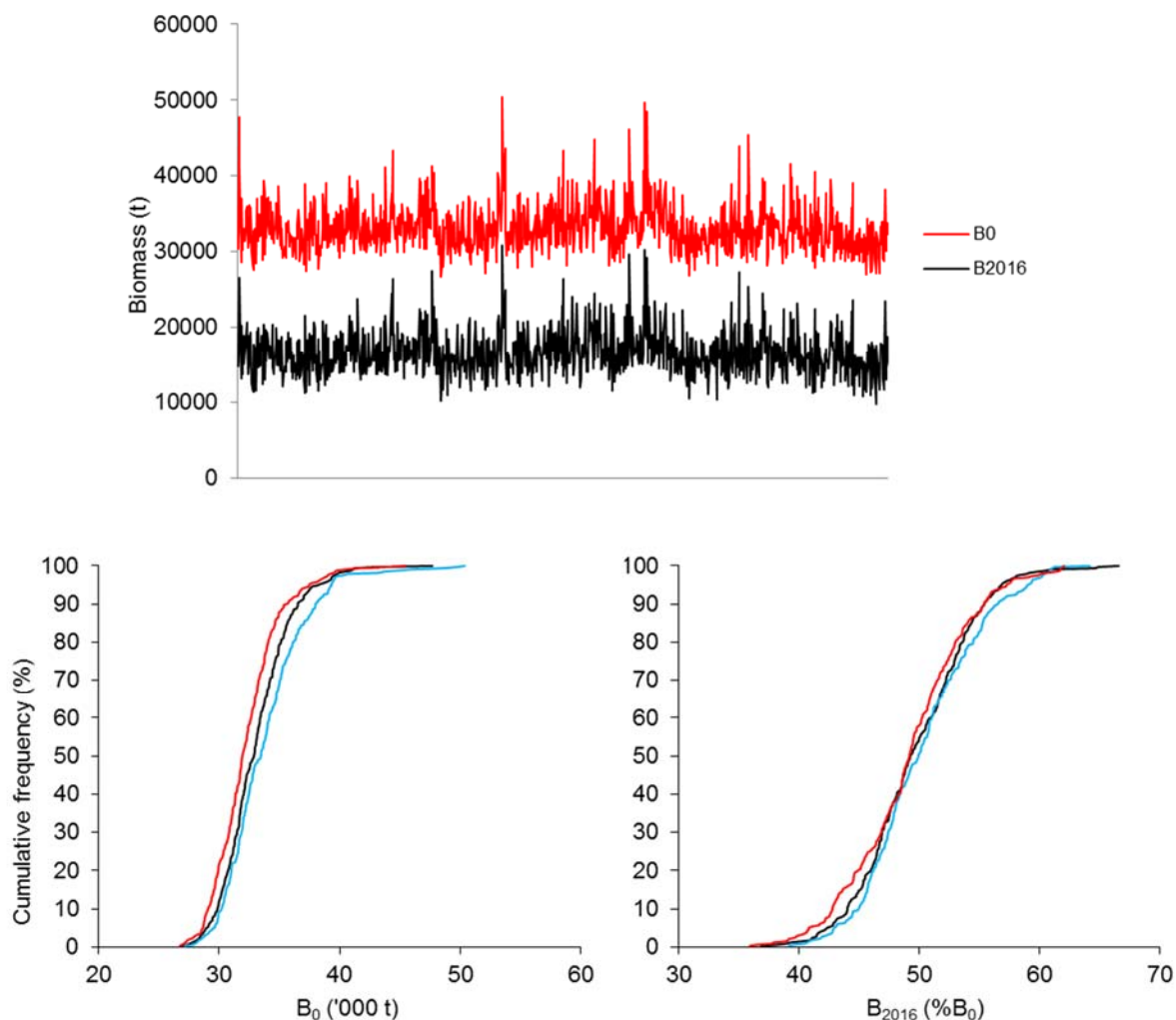


Figure 17: Trace diagnostic plot of the MCMC chains for estimates of B_0 and B_{2016} for the base model run (upper panel). MCMC diagnostic plots showing the cumulative frequencies of B_0 and B_{2016} (% B_0) for the first (black line), middle (blue line), and last (red line) third of the MCMC chain for the base model (lower panel).

The estimated MCMC marginal posterior distributions for selected parameters from the base case model are shown in Figures 18–22. The estimated research survey catchability constant was estimated to be about 0.11, suggesting that the absolute catchability of the survey series was low, but quite consistent with the prior (Figure 18). The MPD fit to the research series in this model run was reasonably good (see Figure 8). The resource survey and fishery selectivity ogives all had relatively wide bounds after age at full selectivity (Figure 19). The prior on age at full selectivity (a_1) for the survey strongly encouraged this parameter to be about 8 ± 2 years (see Figure 7); it was estimated to be about 9 years, thus being more consistent with a visual examination of the survey catch-at-age data. In the western fishery, hake were fully selected from age 8, while full selectivity did not occur until about age 12 in the eastern fishery; this is plausible given that the eastern fishery concentrates more on the spawning biomass (i.e., older fish).

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 the model estimated a period of generally higher than average recruitment (Figure 20). More recent year class strengths appear to be moderately well estimated, being relatively strong in the early 1990s, followed by a period of steadily declining recruitment to about 2000. The 2002 year class was strong, but it has been followed by relatively weak year classes. The strength of the 2002 year class was strongly supported by data from

the research survey series age distributions (Horn 2013b). The 2011 year class was also estimated to be strong.

Estimated spawning stock biomass for the Chatham stock increased throughout the 1980s, owing to the relatively good spawning success during the late 1970s (Figure 21). Biomass then steadily declined from 1989 to 2006 in response to higher levels of exploitation, and generally poor spawning success. The slight increase since 2006 was probably a consequence of the strong 2002 year class, in combination with low levels of fishing pressure since about 2010 (Figure 22). Lower bounds for the spawning biomass estimates were reasonably tight, but the upper bounds were less well determined. Current stock size was about 49% of B_0 with a relatively narrow 95% credible interval of 41–60% (see Figure 21 and Table 14.) Exploitation rates (catch over vulnerable biomass) were very low up to the early 1990s, then were moderate (0.10 – 0.25 yr^{-1}) between 1995 and 2005, but generally low again since 2006 (Figure 22).

Table 14: Bayesian median and 95% credible intervals of B_0 , B_{2016} , and B_{2016} as a percentage of B_0 for the Chatham Rise model runs.

Model run	B_0	B_{2016}	$B_{2016} (\%B_0)$
Base case	32 620 (28 420–39 600)	16 000 (11 770–23 120)	49.4 (40.9–59.8)
Free survey ogive	30 080 (26 510–40 090)	14 540 (10 850–22 460)	48.2 (40.0–59.1)
Estimate M	32 500 (27 440–47 110)	19 020 (13 160–33 220)	58.0 (46.2–74.0)
CPUE	36 910 (30 760–64 230)	20 160 (14 910–40 510)	54.5 (46.8–64.7)

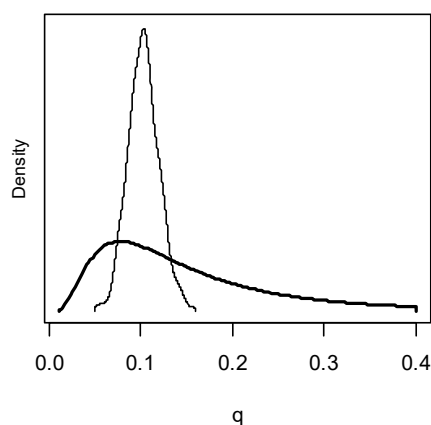


Figure 18: Base case — Estimated posterior distribution (thin line) and prior (thick line) of survey catchability constant q for the Chatham Rise January resource survey series.



Figure 19: Base case — Estimated median selectivity ogives (with 95% credible intervals shown as dashed lines) for the trawl survey series, the western fishery and the eastern fishery, for the Chatham Rise stock.

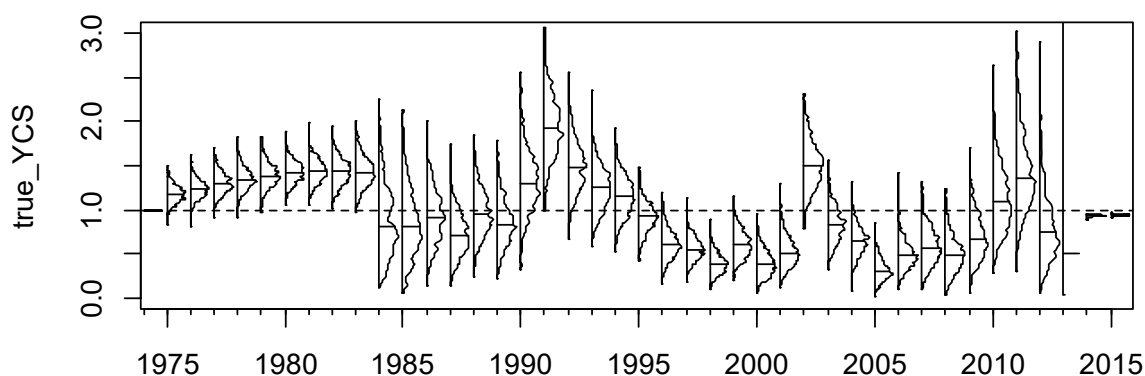


Figure 20: Base case — Estimated posterior distributions of year class strengths for the Chatham Rise stock. The dashed horizontal line indicates the year class strength of one. Individual distributions are the marginal posteriors, with horizontal lines indicating the median.

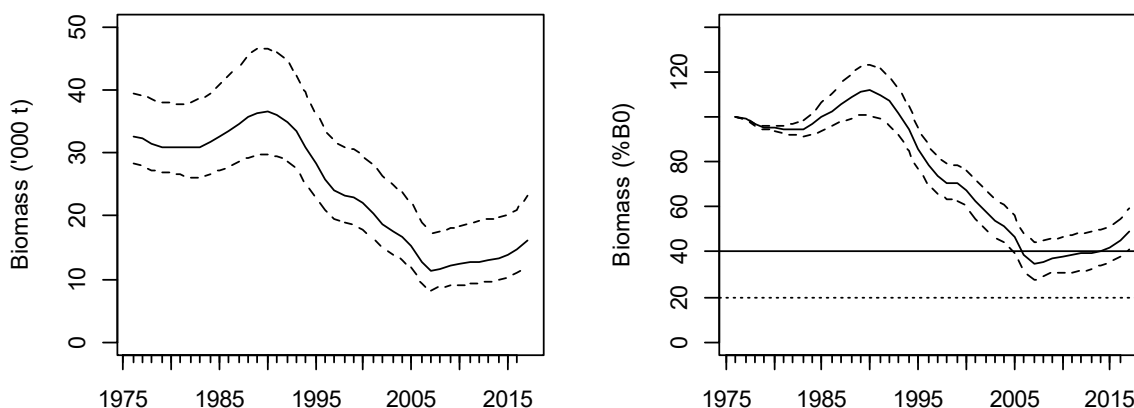


Figure 21: Base case — Estimated median trajectories (with 95% credible intervals shown as dashed lines) for absolute spawning biomass and biomass as a percentage of B_0 , for the Chatham Rise stock. Horizontal lines in the right panel show the management target of 40% B_0 and the soft limit of 20% B_0 .

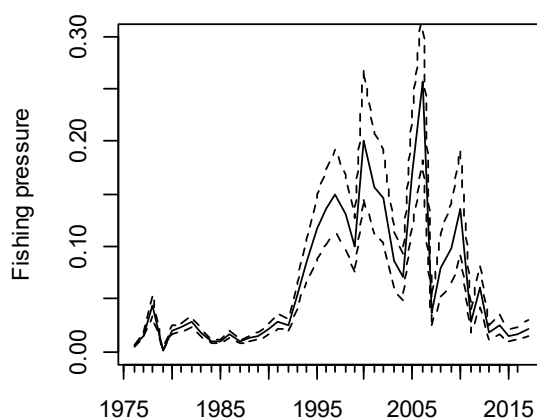


Figure 22: Base case — Estimated median trajectory of exploitation rate (with 95% credible intervals shown as dashed lines).

The ‘Free survey ogive’ sensitivity run differed from the base case in that it had no restriction on the resource survey age at full selectivity. The estimated MCMC marginal posterior distributions for selected parameters from the free survey ogive model are shown in Figures 23–25. This model indicated slightly lower spawning biomass levels than the base case. Accordingly, the estimated research survey catchability constant of about 16% suggested that the absolute catchability of the trawl survey series was higher than that estimated in the base case, and thereby less consistent with the prior (Figure 23). The two fishery selectivity ogives were similar to those from the base case, but the trawl survey ogive was domed rather than principally logistic (Figure 24). The survey selectivity ogive peaked at about age 17 which, as noted above, did not appear to be consistent with a visual examination of the data; they indicated that hake were fully selected by the research gear from about age 8. Fishing selectivities indicated that hake were fully selected in the western fisheries by about age 7 years, compared to age 11 in the eastern fishery.

There was little difference between the base case and free survey ogive models in the estimated pattern or absolute size of year class strengths. Trends in biomass were also similar between models. However, absolute biomass was lower in the free survey ogive model, and current stock status ($B_{2016} = 48\%$ of B_0) was slightly less optimistic (Figure 25, Table 14).

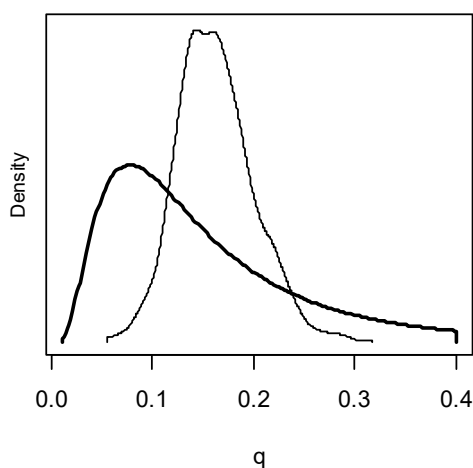


Figure 23: Free survey ogive — Estimated posterior distribution (thin line) and prior (thick line) of survey catchability constant q for the Chatham Rise January resource survey series.



Figure 24: Free survey ogive — Estimated median selectivity ogives (with 95% credible intervals shown as dashed lines) for the trawl survey series, the western fishery and the eastern fishery.

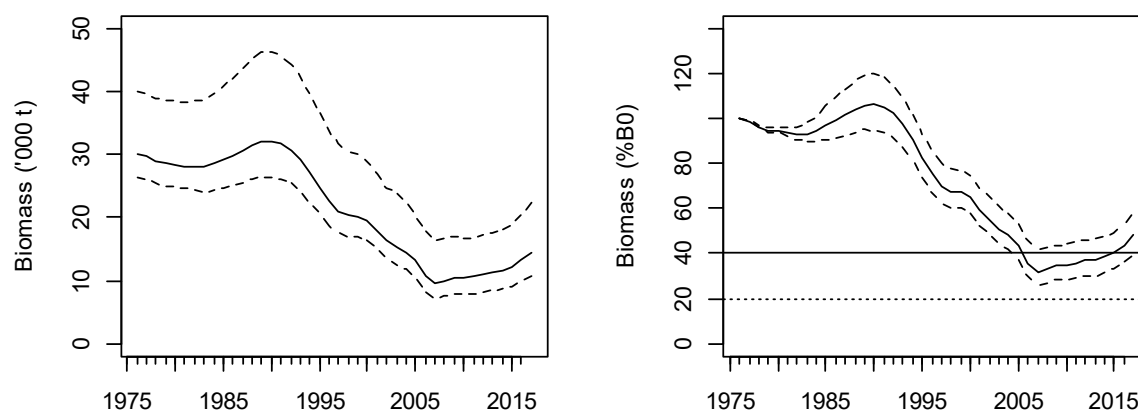


Figure 25: Free survey ogive — Estimated median trajectories (with 95% credible intervals shown as dashed lines) for absolute spawning biomass and biomass as a percentage of B_0 , for the Chatham Rise stock. Horizontal lines in the right panel show the management target of 40% B_0 and the soft limit of 20% B_0 .

The ‘Estimate M ’ sensitivity run differed from the free survey ogive model in that M was estimated as an age-independent constant (rather than being assumed constant at 0.19). The estimated median M was 0.25, with a 95% credible interval of 0.21–0.29, and the posterior distribution was not particularly consistent with the prior (Figure 26). The selectivity ogives for the trawl survey and two fisheries were all principally logistic (even though all fitted using double-normal parameterisation), and the issue with the trawl survey age at peak selectivity being unreasonably high remained (Figure 27). Year class strength estimates were virtually identical to those from the base case. The absolute biomass trajectory had broader bounds, and stock status was markedly more optimistic than that from the base case (58% B_0 compared with 49%) (Figure 28, Table 14).

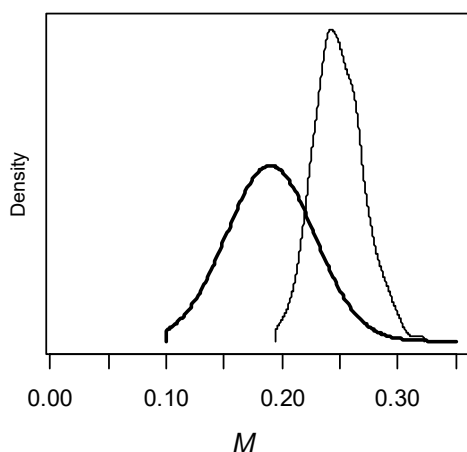


Figure 26: Estimate M — Estimated posterior distribution (thin line) and prior (thick line) of instantaneous natural mortality, M .



Figure 27: Estimate M — Estimated median selectivity ogives (with 95% credible intervals shown as dashed lines) for the trawl survey series, the western fishery and the eastern fishery.

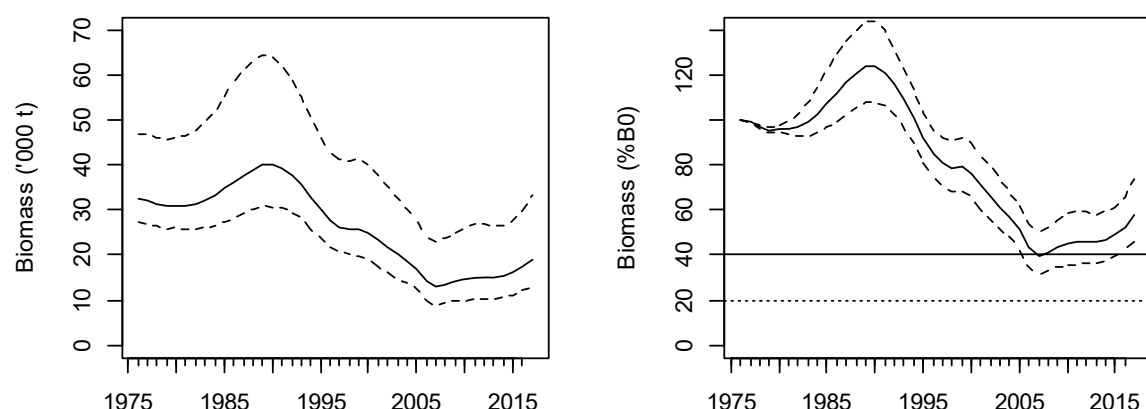


Figure 28: Estimate M — Estimated median trajectories (with 95% credible intervals shown as dashed lines) for absolute spawning biomass and biomass as a percentage of B_0 , for the Chatham Rise stock. Horizontal lines in the right panel show the management target of 40% B_0 and the soft limit of 20% B_0 .

The ‘CPUE’ sensitivity run differed from the free survey ogive model in that the eastern trawl fishery CPUE was included as an additional relative abundance series. The estimated year class strengths were very similar to those from the base and free survey ogive models. The fishery selectivity ogives were little different to those from the free survey ogive model, but the median trawl survey selectivity ogive was principally logistic (rather than domed) and had full selectivity at about age 10 years (rather than about 16) (Figure 29). All three selectivity ogives were little different to those from the base model. It was not apparent why the inclusion of the CPUE series largely removed the issue of the high age at full selectivity for the research survey.



Figure 29: CPUE — Estimated median selectivity ogives (with 95% credible intervals shown as dashed lines) for the trawl survey series, the western fishery and the eastern fishery.

At MPD, the CPUE series was well-fitted (see Figure 13), but the inclusion of CPUE in the model did result in a slight degradation of the fits to the survey biomass series (the objective function increased by about 1) and the fishery catch-at-age data (the objective function increased by about 3).

The biomass trends were similar to the base and free survey ogive models, but with an overall flatter trajectory, and with relatively wide confidence bounds (Figure 30). However, relative to the base case, absolute spawning biomass estimates are markedly higher, and stock status was also higher (Table 14).

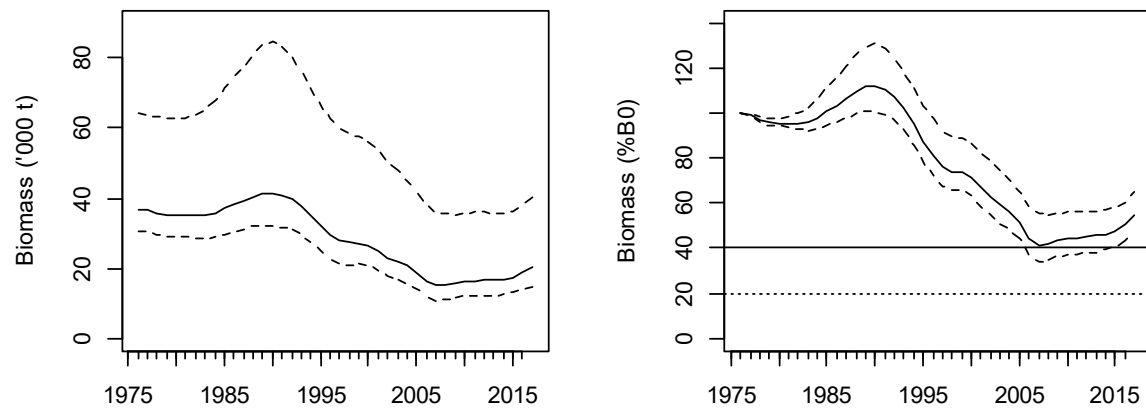


Figure 30: CPUE — Estimated median trajectories (with 95% credible intervals shown as dashed lines) for absolute spawning biomass and biomass as a percentage of B_0 , for the Chatham Rise stock. Horizontal lines in the right panel show the management target of 40% B_0 and the soft limit of 20% B_0 .

5.4 Biomass projections

Spawning stock biomass projections from all models were made assuming two future catch scenarios; either 400 t or 1800 t annually from 2017 to 2021. The higher catch level was the TACC for HAK 4. It was much higher than recent annual landings from the stock, but lower than what could be taken if all the HAK 4 TACC, plus some HAK 1 catch from the western Rise, was taken. The lower catch level (400 t) was equivalent to the average annual catch that had been taken in the last six years.

In the projections, relative year class strengths from 2014 onwards were selected randomly from the previously estimated year class strengths from 1984 to 2013.

Projections from all the model runs suggested that spawning biomass would change little between 2016 and 2021 if annual catches increased to the level of the HAK 4 TACC (Table 15, Figure 31). If future catches remained at recent levels the spawning biomass was projected to increase by about 20–30% by 2021 (Table 15).

Table 15: Bayesian median and 95% credible intervals of projected B_{2021} , B_{2021} as a percentage of B_0 , and B_{2021}/B_{2016} (%) for the Chatham Rise model runs.

Model run	Future catch (t)		B_{2021}	$B_{2021} (\%B_0)$	$B_{2021}/B_{2016} (\%)$
Base	1 800	16 560	(9 980–26 260)	50.3 (33.8–70.1)	101 (77–132)
	400	21 180	(14 810–31 800)	64.9 (49.2–84.1)	130 (107–160)
Free survey ogive	1 800	14 700	(8 850–25 600)	48.3 (32.3–69.6)	100 (75–132)
	400	19 170	(13 620–30 280)	63.7 (48.9–83.4)	132 (108–162)
Estimate M	1 800	19 490	(11 570–35 640)	59.5 (39.9–87.0)	102 (78–133)
	400	23 770	(15 570–38 720)	72.5 (53.9–95.9)	124 (99–156)
CPUE	1 800	21 010	(13 240–44 050)	56.6 (40.4–78.2)	103 (79–136)
	400	25 580	(17 920–49 950)	68.7 (54.7–89.3)	126 (104–156)

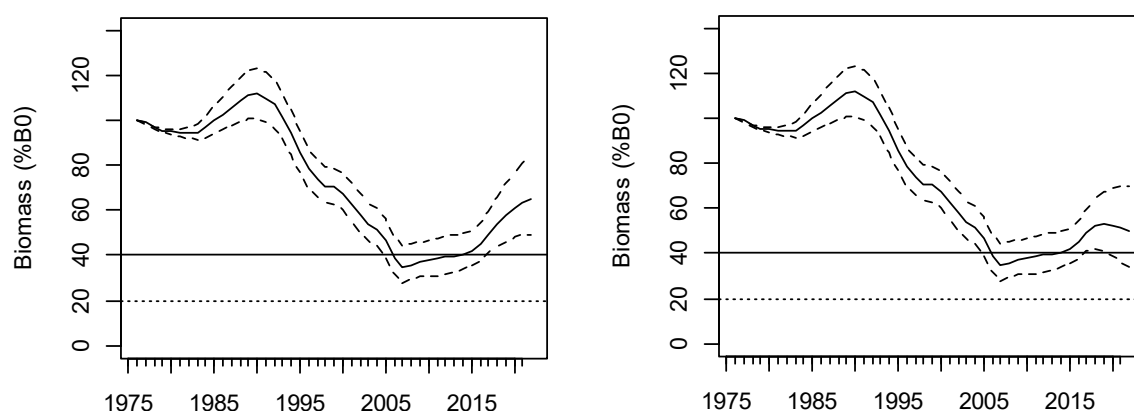


Figure 31: Base case — Estimated median trajectories (with 95% credible intervals shown as dashed lines) for spawning biomass as a percentage of B_0 , for the Chatham Rise stock, projected to 2021 with future catches assumed to be 400 t (left panel) and 1800 t (right panel) annually. Horizontal lines show the management target of 40% B_0 and the soft limit of 20% B_0 .

5.5 Management biomass targets

Probabilities that current and projected spawning biomass would drop below selected management reference points (i.e., target, 40%B₀; soft limit, 20%B₀; hard limit, 10%B₀) are shown for the base model and all sensitivity runs in Table 16. All models indicated that it was extremely unlikely (i.e., less than a 1% chance) that B₂₀₂₁ would be lower than the soft target of 20%B₀ both with catches maintained at the recent level, or if they increased to the level of the HAK 4 TACC. It was also unlikely (i.e., less than a 20% chance) that B₂₀₂₁ would be lower than 40% B₀ with future annual catches of 1800 t.

Table 16: Probabilities that current (B₂₀₁₆) and projected (B₂₀₂₁) spawning biomass will be less than 40%, 20% or 10% of B₀. Projected biomass probabilities are presented for a future annual catch of 400 t and 1800 t.

Model run	Biomass	Management reference points		
		40% B ₀	20% B ₀	10% B ₀
Base case	B ₂₀₁₆	0.016	0.000	0.000
	B ₂₀₂₁ , 1800 t catch	0.125	0.000	0.000
	B ₂₀₂₁ , 400 t catch	0.000	0.000	0.000
Free survey ogive	B ₂₀₁₆	0.027	0.000	0.000
	B ₂₀₂₁ , 1800 t catch	0.179	0.000	0.000
	B ₂₀₂₁ , 400 t catch	0.000	0.000	0.000
Estimate <i>M</i>	B ₂₀₁₆	0.000	0.000	0.000
	B ₂₀₂₁ , 1800 t catch	0.028	0.000	0.000
	B ₂₀₂₁ , 400 t catch	0.000	0.000	0.000
CPUE	B ₂₀₁₆	0.000	0.000	0.000
	B ₂₀₂₁ , 1800 t catch	0.021	0.000	0.000
	B ₂₀₂₁ , 400 t catch	0.000	0.000	0.000

6. MODEL ESTIMATES FOR WCSI HAKE

6.1 Developing a ‘base’ model

Some initial MPD investigations were completed to develop a ‘base’ model. The initial structure of the model followed previous assessments which had investigated model assumptions relating to survey selectivity, fishery selectivity, and estimation of natural mortality rate (Horn 2013b). Final model parameters were estimated using Bayesian estimation implemented using the CASAL software.

An initial model run (model 1) was set up, with the partition excluding sex and maturity. Both available relative abundance series (the trawl survey, and CPUE) were included. The model estimated selectivity ogives for the commercial fishery and the trawl survey using the double-normal parameterisation. Selectivities were assumed constant over all years. A constant value of 0.19 was used for *M*. The CPUE series was reasonably well fitted, but the recent declining trend in the trawl survey index was poorly fitted (Figure 32).

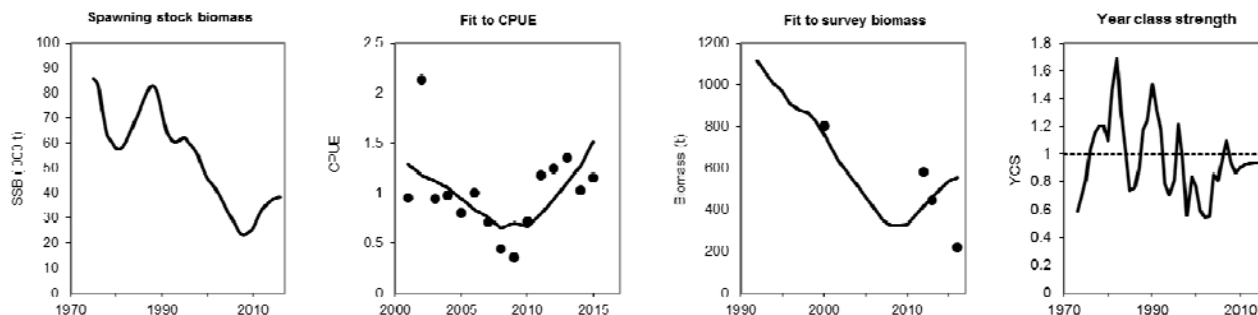


Figure 32: Biomass trajectory, fits to the trawl fishery CPUE and trawl survey series, and estimated year class strengths, from model 1.

Two additional models examined the impact of using the CPUE series, but not the trawl survey data (model 2), and the trawl survey data, but not the CPUE series (model 3). There were marked differences between these two models in the biomass trajectories and year class strength estimates (Figures 33 and 34). Clearly there is a conflict between the two relative abundance indices. The trawl survey indicated a recent declining biomass with current biomass being lower than in 2000, whereas the CPUE indicated a recent increase in biomass and a current level similar to that in 2000. The difference between the two model runs was the biomass index plus the inclusion (or exclusion) of the survey catch-at-age data. It appears likely that the choice of biomass index was also influencing the year class strength estimates (at least at MPD), although the survey catch-at-age data would also have some influence. Consequently, it is important to consider whether we can justify one series as being more plausible than the other. It is generally held that where a fishery-independent series (e.g., a trawl survey) is available, then the model should fit to it in preference to a CPUE series, which is subject to greater potential biases. However, this trawl survey series was relatively sparse and did not survey the entire area off WCSI where hake are known to be relatively abundant. The CPUE series was also not without problems: it was truncated (at 2001) because earlier data were considered unreliable and biased (Ballara 2013), and there may still be biases in the series since 2001. In particular, changes in fishing technology and in the commercial (economic) desirability of hake are not captured in the QMS effort statistics, and so cannot be standardised for in any CPUE model.

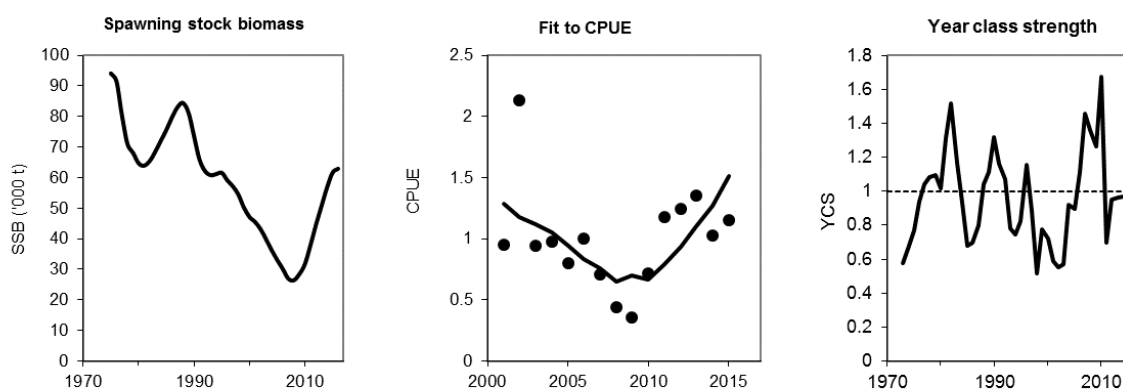


Figure 33: Biomass trajectory, fits to the trawl fishery CPUE series, and estimated year class strengths, from model 2.

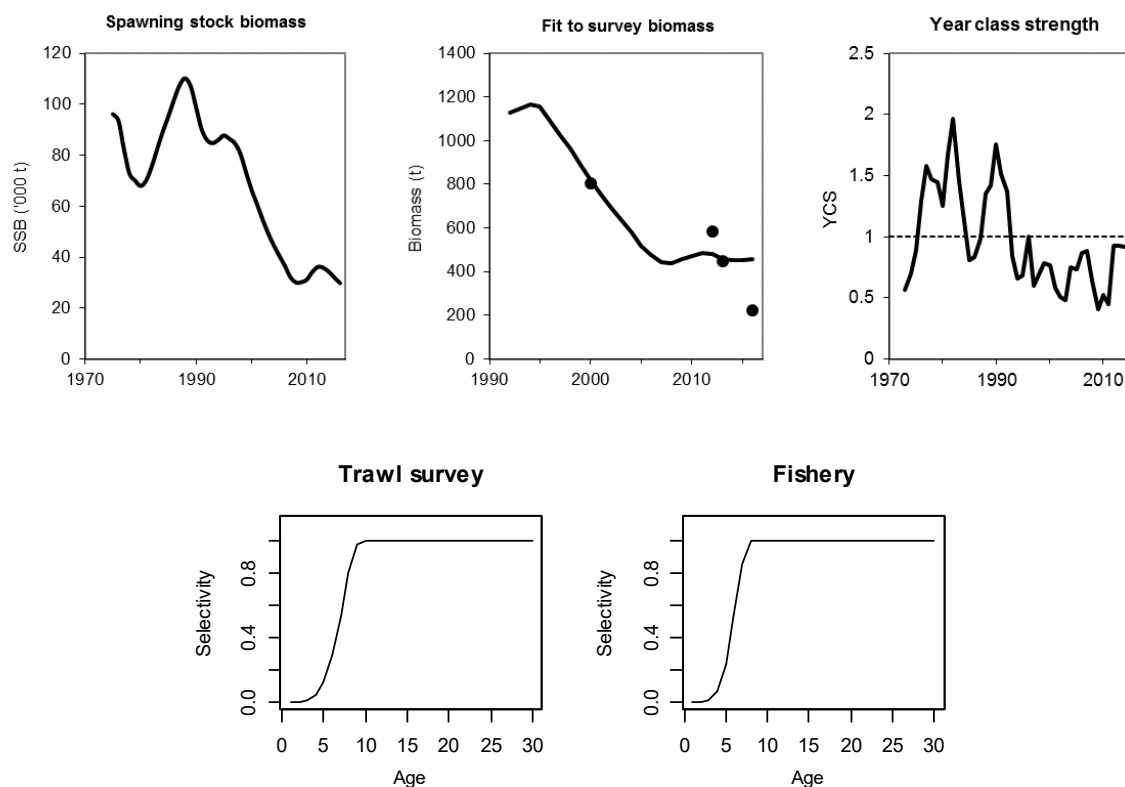


Figure 34: Biomass trajectory, fits to the trawl survey series, estimated year class strengths, and selectivity ogives from model 3.

A likelihood profile for model 1 (the model which includes all the available data sets) showed that the research survey encouraged a low B_0 (less than 60 000 t), whereas the CPUE encouraged a value between 120 000 and 130 000 t (Figure 35). The age data from the trawl survey and the fishery encouraged a B_0 in the range 80 000–100 000 t. The CPUE and survey age data strongly discouraged a B_0 less than about 70 000 t.

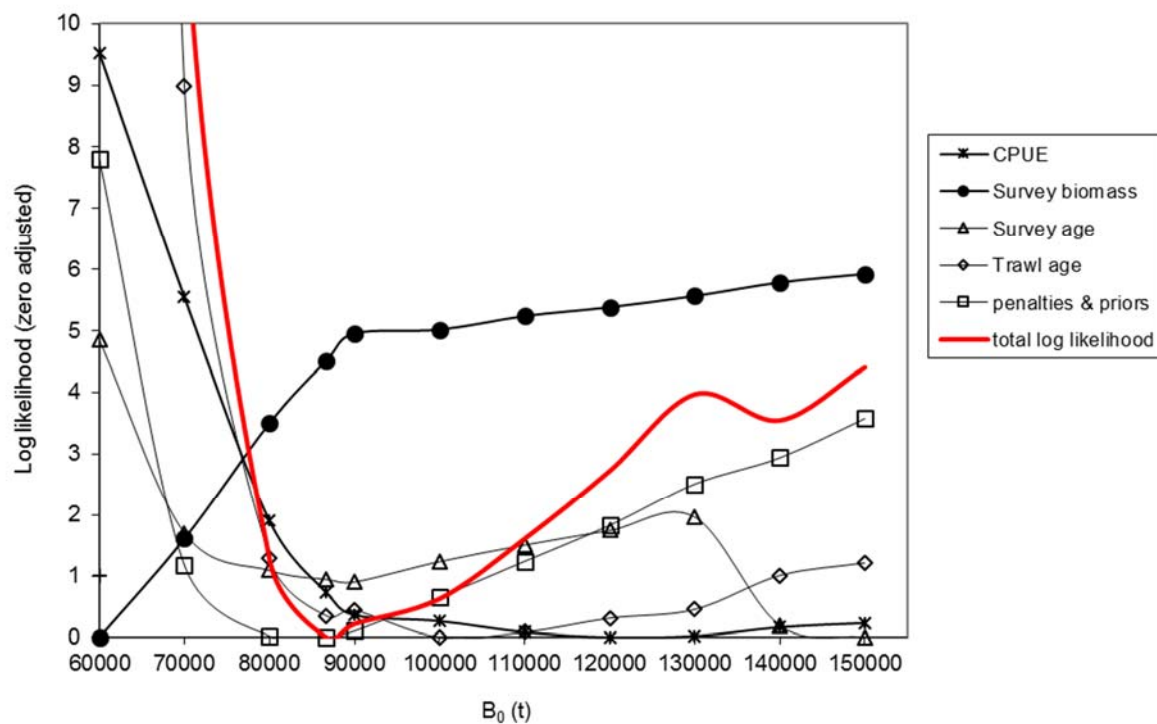


Figure 35: Likelihood profile (smoothed lines) on B_0 for model 1, showing both the total likelihood (red line) and those for individual data series.

The catch-at-age data from the trawl survey and trawl fishery in model 1 were reasonably well fitted (Figures 36 and 37). There was little visible difference in fits across all of the three models trialed.

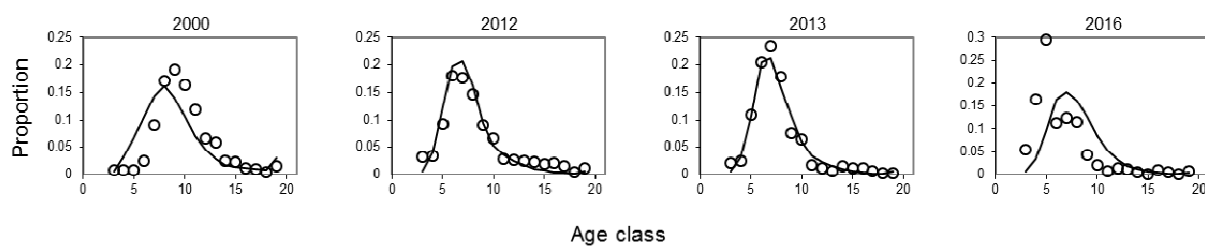


Figure 36: Fits (lines) to the research trawl survey proportion-at-age distributions (circles), from model 1.

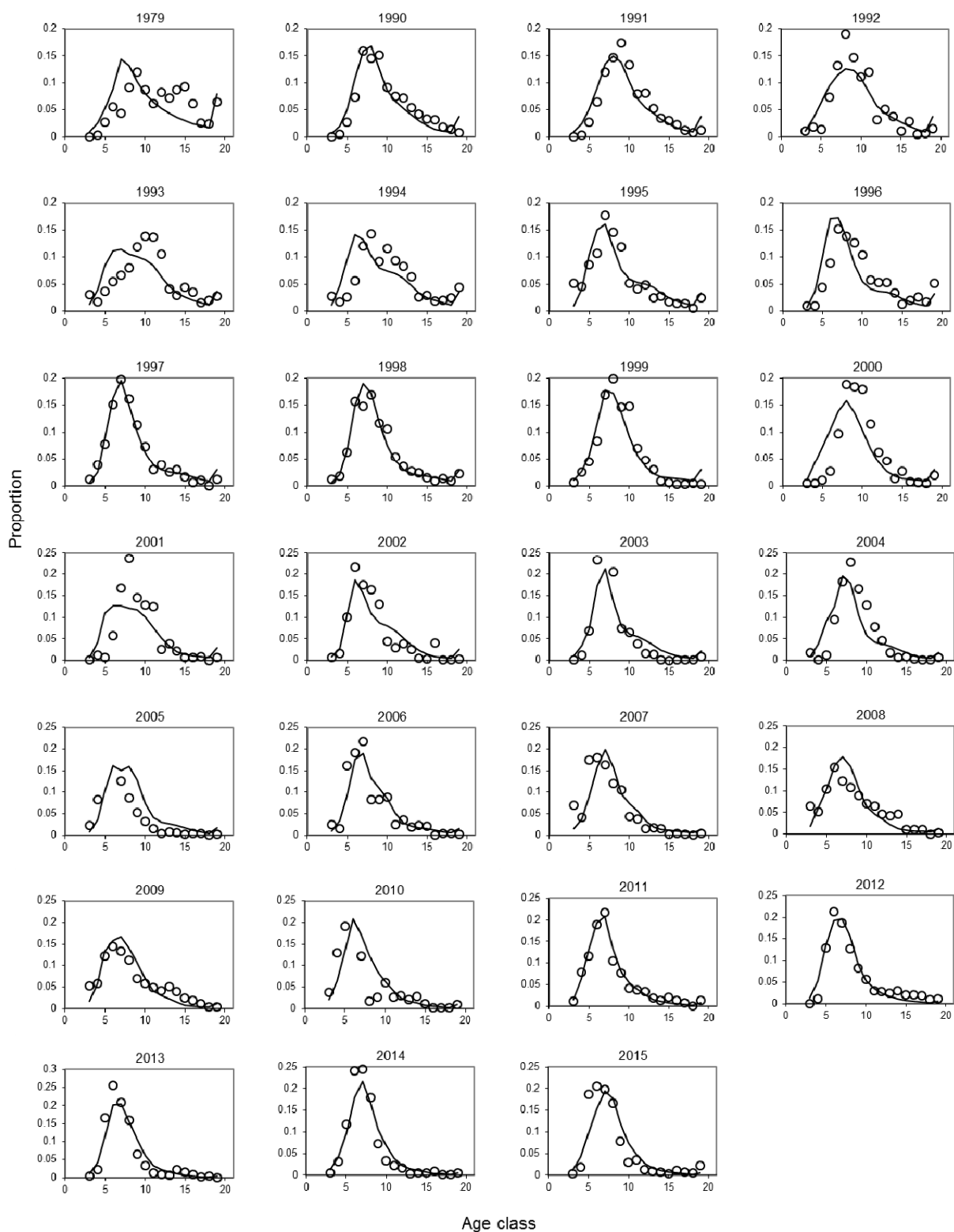


Figure 37: Fits (lines) to the trawl fishery proportion-at-age distributions (circles), from model 1.

Model 4 was the same as model 1 except that M was estimated as a double-exponential ogive. Compared to model 1, the fits to the trawl survey and CPUE series were virtually identical. The biomass trajectory was slightly lower (Figure 38), and there was a slight improvement in the fits to the fishery age data (the objective function decreased by 4.3). The estimated M ogive was considered plausible, although it had a

relatively low trough of 0.06 yr^{-1} for a 6 year-old fish (Figure 38). The survey and fishery selectivity ogives were logistic shaped despite being estimated using the double-normal parameterisation.

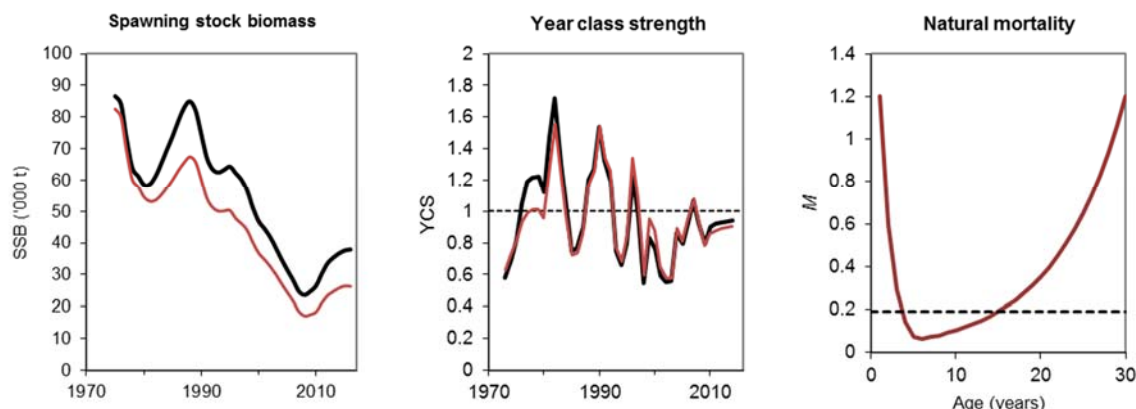


Figure 38: Biomass trajectory, estimated year class strengths, and estimated natural mortality ogive, from model 1 (black lines) and model 4 (red lines).

Model 5 was the same as Model 1 except that it included sex in the partition, had sexed catch-at-age data, and had separate growth curves for males and females. The model estimated a higher SSB, but negligible changes to the CPUE and trawl survey biomass fits and estimated year class strengths (Figure 39). The selectivity ogives were markedly different between sexes, but it was not known if these differences were plausible (Figure 40).

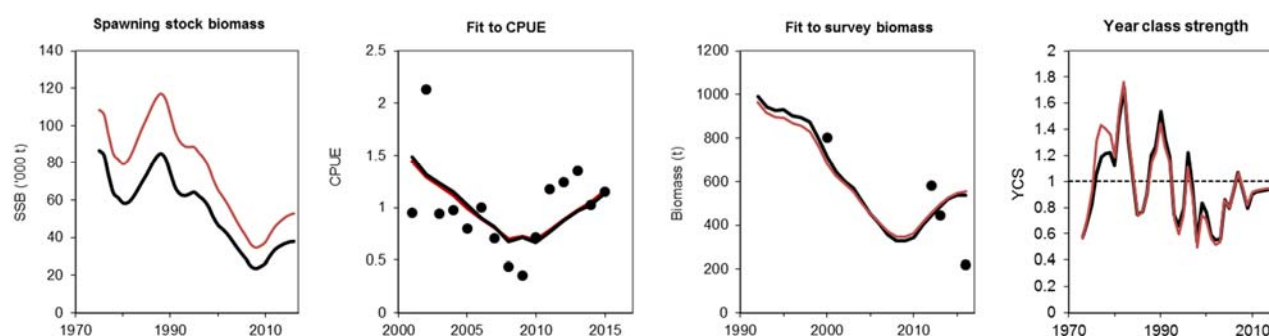


Figure 39: Biomass trajectory, fits to the CPUE and trawl survey biomass indices, and estimated year class strengths, from model 1 (black lines) and model 5 (red lines).

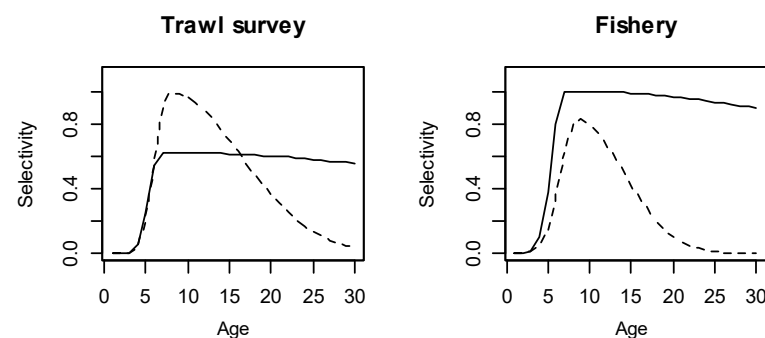


Figure 40: Estimated selectivity ogives (solid lines for males, broken lines for females) for the research survey and two commercial fisheries from model 5.

Following MPD investigations, the Deepwater Fisheries Working Group concluded that a single base case model could not be identified as there was no clear preference to place greater reliance on either the trawl survey or CPUE data series. Consequently, MCMC estimates were produced for model 3 (trawl survey data, no CPUE data, with a constant M of 0.19 yr^{-1} ; the “Survey model”) and model 2 (CPUE data, no trawl survey data, with a constant M of 0.19 yr^{-1} ; the “CPUE model”), and both these were reported in the MPI Plenary Document. A sensitivity variation to the trawl survey model estimating M as an age-invariant constant (the “Estimate M ” model) was also included.

6.2 Model estimation using MCMC

Model parameters were estimated using Bayesian estimation implemented using the CASAL software. For final runs, the full posterior distribution was sampled using Monte Carlo Markov Chain (MCMC) methods, based on the Metropolis-Hastings algorithm. 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).

6.3 MCMC estimates

Estimates of the posterior distribution were obtained and are presented below. In addition, MCMC estimates of the median posterior and 95% percentile credible intervals are reported for the key output parameters. The MCMC chains for estimates of B_0 and B_{2016} from the survey model showed no strong signs of non-convergence (Figure 41). The distributions of estimates of B_0 and B_{2016} (as % B_0) from the base model were consistent between the first, middle, and last thirds of the chain (Figure 41), and parameter estimates were considered adequate for stock assessment purposes.

The estimated MCMC marginal posterior distributions for selected parameters from the survey model are shown in Figures 42–46. The median selectivity ogives for both the survey and the fishery were approximately logistic, and had relatively narrow credible intervals (Figure 42). The ogives suggested that hake were fully selected by the fishery by about age 9, and slightly older in the survey. Given that the survey uses a smaller codend mesh than the fishery, these ages at full selectivity are the reverse of what would be expected. The estimated research survey catchability constant was estimated to be about 0.04, suggesting that the absolute catchability of the survey series was low, although consistent with the prior (Figure 43).

Variation in year class strength did not appear to be great (Figure 44); virtually all median estimates were between 0.5 and 2. The last 12 estimated year class strengths (1998–2009) were all lower than average.

Estimated spawning biomass for the WCSI stock declined throughout the late 1970s with relatively high catch levels, then increased through the mid 1980s concurrent with a marked decline in catch (Figure 45). Spawning biomass then steadily declined from 1988 to about 2010, with a higher level of exploitation and year class strengths that were generally below average. The estimated biomass trajectory was flat after 2010. Credible intervals around the biomass estimates were reasonably tight, with current stock size being about 26% B_0 (95% credible interval 19–37%) (see Figure 45 and Table 17). Exploitation rates (catch over vulnerable biomass) were less (often much less) than 0.2 up until 2000 (except in 1977), but were moderate ($0.2\text{--}0.4 \text{ yr}^{-1}$) since then (Figure 46). The exploitation rate in 2015 was the highest estimated for any year.

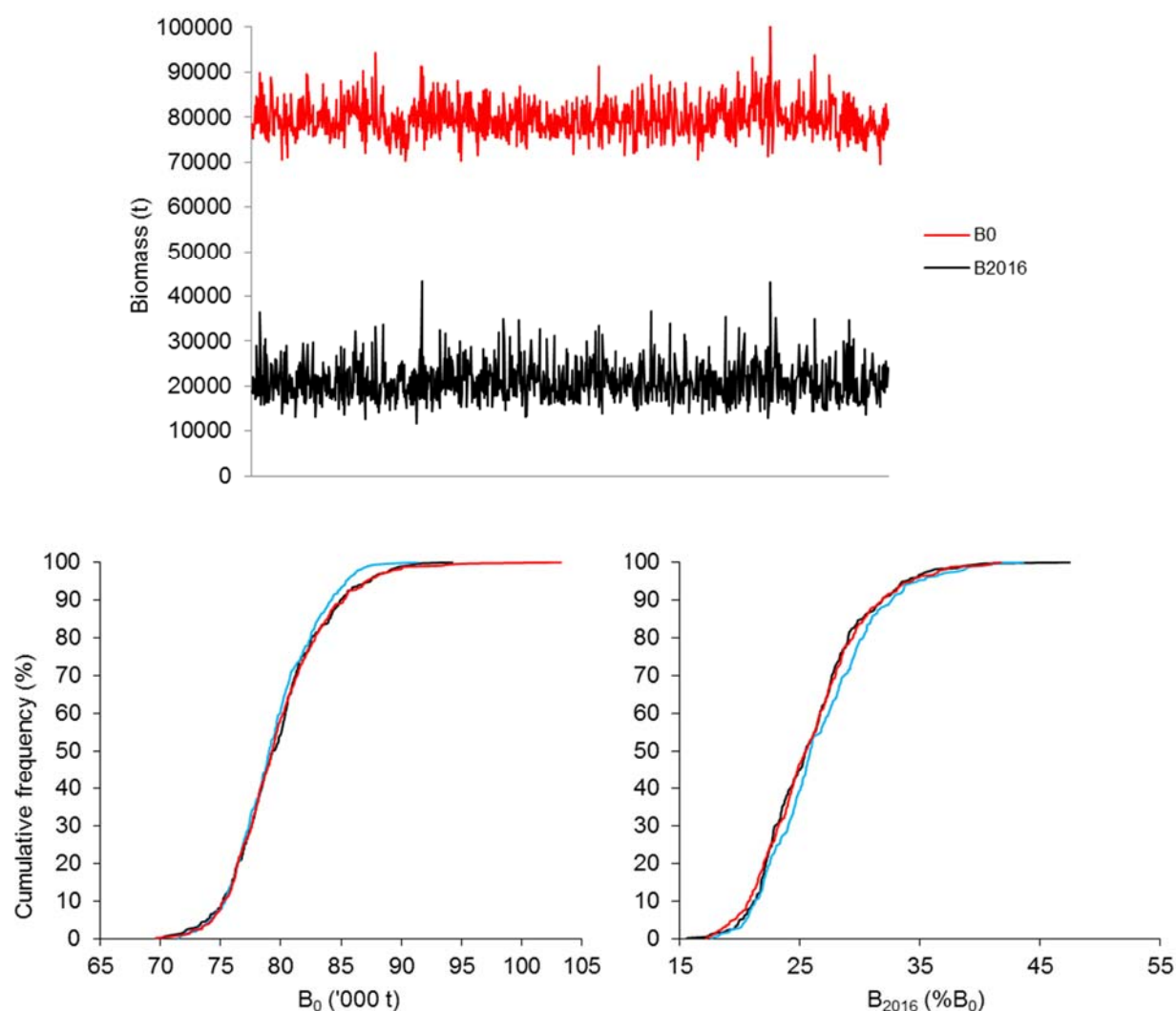


Figure 41: Trace diagnostic plot of the MCMC chains for estimates of B_0 and B_{2016} for the survey model run (upper panel). MCMC diagnostic plots showing the cumulative frequencies of B_0 and B_{2016} ($\%B_0$) for the first (black line), middle (blue line), and last (red line) third of the MCMC chain for the base model (lower panel).

Table 17: Bayesian median and 95% credible intervals of B_0 , B_{2016} , and B_{2016} as a percentage of B_0 for all model runs.

Model run	B_0		B_{2016}		B_{2016} ($\%B_0$)
Survey	79 190	(73 000–87 990)	20 490	(14 640–30 880)	25.7 (19.1–36.5)
Estimate M	80 430	(73 950–91 670)	20 500	(12 220–35 740)	25.6 (15.6–40.9)
CPUE	92 100	(81 410–131 360)	46 550	(29 190–87 710)	50.3 (34.6–73.6)

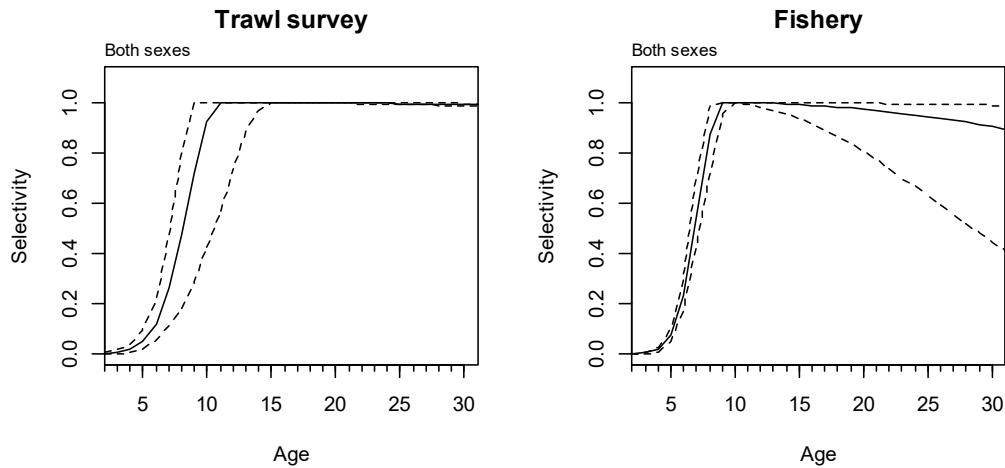


Figure 42: Survey Model — Estimated median selectivity ogive (with 95% credible intervals shown as dashed lines) for the trawl survey and the commercial trawl fishery.

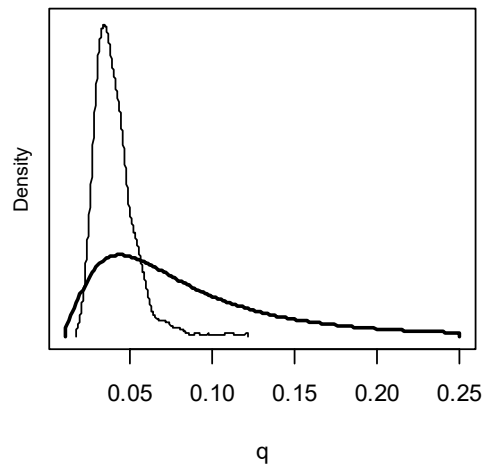


Figure 43: Survey Model — Estimated posterior distribution (thin line) and prior (thick line) of survey catchability constant q for the WCSI winter resource survey series.

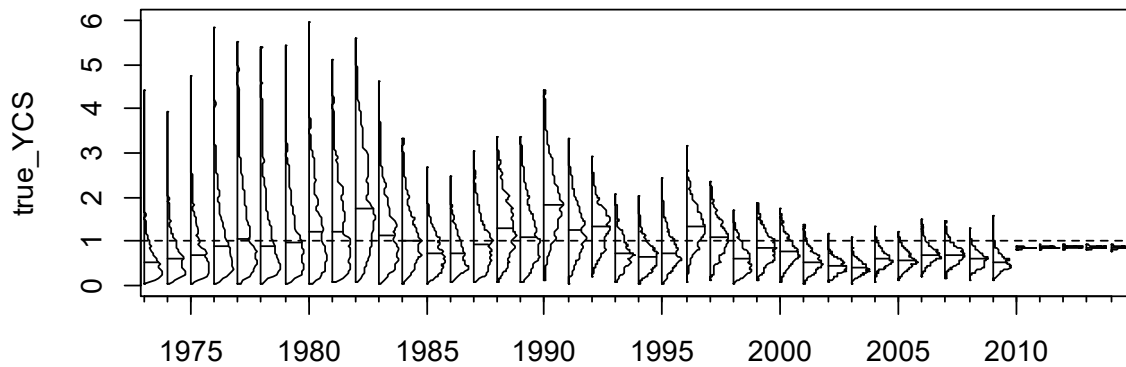


Figure 44: Survey Model — Estimated posterior distributions of year class strengths. The dashed horizontal line indicates the year class strength of one. Individual distributions are the marginal posteriors, with horizontal lines indicating the median.

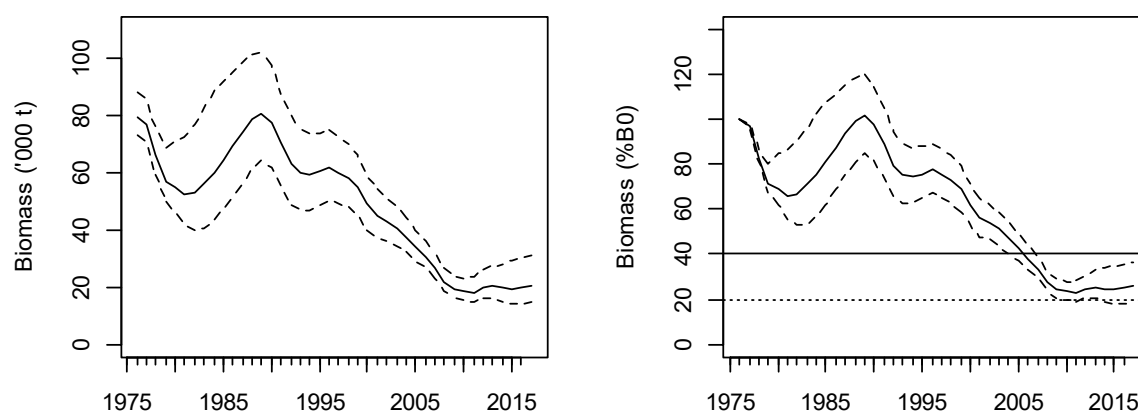


Figure 45: Survey Model — Estimated median trajectories (with 95% credible intervals shown as dashed lines) for absolute spawning biomass and biomass as a percentage of B_0 . Horizontal lines in the right panel show the management target of 40% B_0 and the soft limit of 20% B_0 .

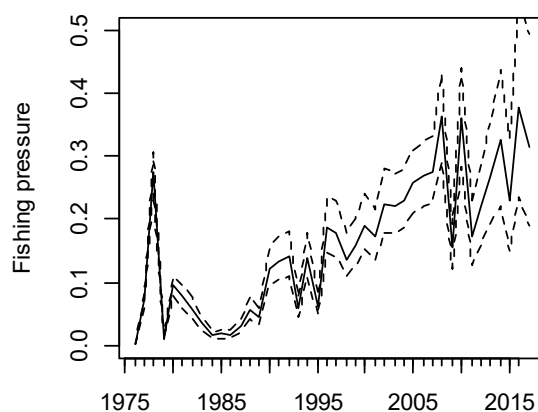


Figure 46: Survey Model — Estimated median trajectory of exploitation rate (with 95% credible intervals shown as dashed lines).

The ‘Estimate M ’ sensitivity run MCMC marginal posterior distributions for selected parameters are shown in Figures 47–49. The estimated median M was 0.19, with a 95% credible interval of 0.15–0.23 (Figure 47). The posterior distribution for M was very consistent with the prior. The selectivity ogives, year class strengths, and exploitation rates were little different to those from the base model (Figure 48).

Trends in biomass, and the estimate of current stock status, were very similar between the survey and estimate M models (Table 16; Figure 49, compared with Figure 45). This is not surprising given that the estimated median M of 0.19 was the same as the constant used in the survey model. However, because of the extra uncertainty added when M was not constant, the credible intervals around the biomass trajectory were wider when M was estimated.

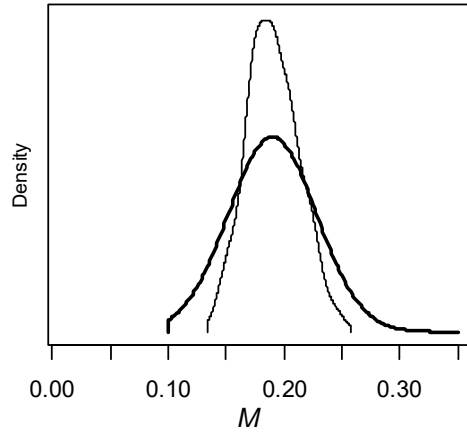


Figure 47: Estimate M — Estimated posterior distribution (thin line) and prior (thick line) of instantaneous natural mortality, M .

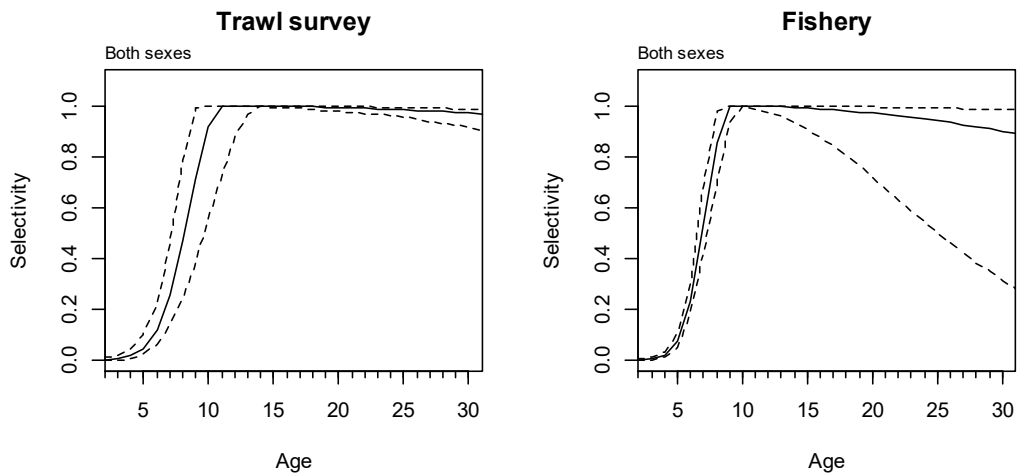


Figure 48: Estimate M — Estimated median selectivity ogives (with 95% credible intervals shown as dashed lines) for the WCSI stock.

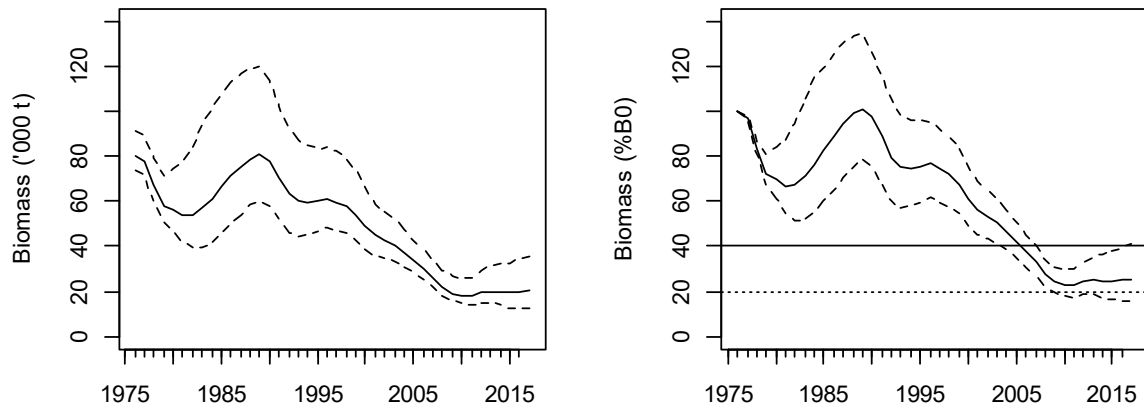


Figure 49: Estimate M — Estimated median trajectories (with 95% credible intervals shown as dashed lines) for absolute spawning biomass and biomass as a percentage of B_0 , for the WCSI stock. Horizontal lines in the right panel show the management target of 40% B_0 and the soft limit of 20% B_0 .

The ‘CPUE’ sensitivity run examined the effect of ignoring the survey data (biomass and proportions-at-age), and using the CPUE series as the index of relative abundance. This model produced results markedly different to those from the survey model, although the fishery selectivity was little different to that from the survey model (Figure 50). The biomass was higher than in the other two model runs, and stock status was markedly higher (i.e., 50% B_0 compared with about 26%) (see Table 16, Figure 51). The estimated year class strengths were higher from the early 2000s than in the survey model, with those from 2006–2009 all estimated to be about average strength (Figure 52). Median exploitation rates (catch over vulnerable biomass) were less (often much less) than 0.2 yr^{-1} in all years except 1977 and 2000–2010, but never exceeded 0.3 yr^{-1} in any year (Figure 53). The exploitation rates since 2011 were estimated to all be about 0.13 yr^{-1} .

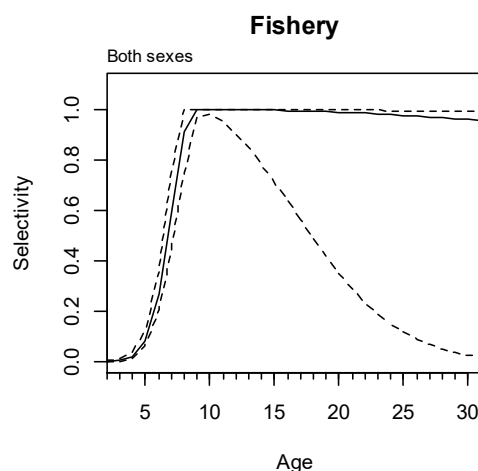


Figure 50: CPUE Model — Estimated median fishery selectivity ogive (with 95% credible intervals shown as dashed lines) for the WCSI stock.

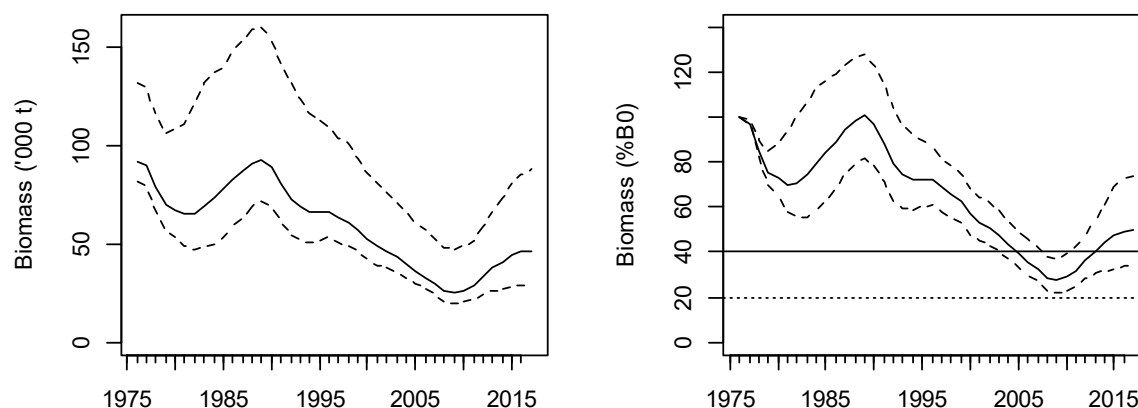


Figure 51: CPUE Model — Estimated median trajectories (with 95% credible intervals shown as dashed lines) for absolute spawning biomass and biomass as a percentage of B_0 , for the WCSI stock.

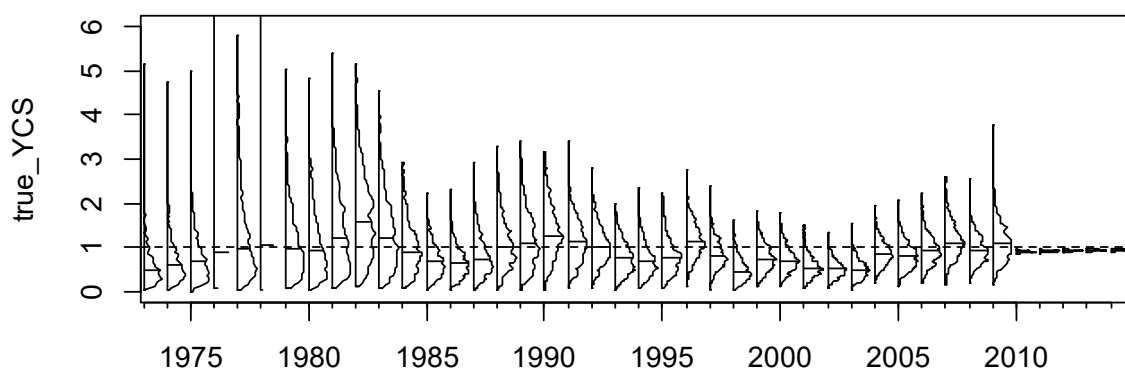


Figure 52: CPUE Model — Estimated posterior distributions of year class strengths. The dashed horizontal line indicates the year class strength of one. Individual distributions are the marginal posteriors, with horizontal lines indicating the median.

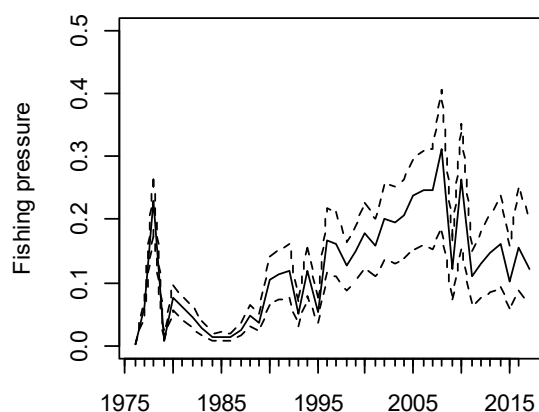


Figure 53: CPUE Model — Estimated median trajectory of exploitation rate (with 95% credible intervals shown as dashed lines).

6.4 Biomass projections

Projections of spawning biomass from the survey and CPUE models were made under two assumed future constant catch scenarios (4100 t or 7700 t annually from 2017 to 2021). The low catch scenario (4100 t) approximated the average catch level from the last six years. The high catch scenario (7700 t) was the highest likely level of catch as it equated to the HAK 7 TACC. In addition, projections were completed under two future recruitment scenarios: year class strengths from 2010 onwards were selected randomly from either 2000–2009 (recent poor recruitment scenario) or 1973–2009 (long-term average recruitment scenario).

Projections indicated that between 2016 and 2021 spawning biomass would decrease under all model scenarios (i.e., by 15–45%) at the higher catch level, but increase under all model scenarios except the ‘poor future recruitment survey model’ at the lower projected catch level (Table 18, Figures 54 and 55). These projections were quite uncertain, however, as indicated by the rapidly spreading confidence intervals after 2016, particularly for the CPUE model. The results were strongly influenced by the relative abundance series used; they were much more pessimistic when using the survey model than when using the CPUE model.

Table 18: Bayesian median and 95% credible intervals of projected B_{2021} , B_{2021} as a percentage of B_0 , and B_{2021}/B_{2016} (%) for the survey and CPUE models, under two future annual catch scenarios, and two future recruitment (YC) scenarios.

Model	Future catch (t)	Future YC	B_{2021}		$B_{2021} (\%B_0)$	$B_{2021}/B_{2016} (\%)$
Survey	4 100	2000–09	14 230	(5 900–30 150)	18.1 (7.4–36.2)	91 (55–133)
	7 700		8 570	(5 160–17 850)	10.8 (6.9–20.8)	55 (34–90)
	4 100	1973–09	28 660	(10 800–56 570)	36.3 (13.7–68.6)	138 (73–261)
	7 700		17 000	(7 180–42 180)	21.4 (9.2–52.0)	84 (39–185)
CPUE	4 100	2000–09	49 010	(26 850–95 210)	52.7 (31.7–87.0)	106 (78–136)
	7 700		36 560	(13 880–78 510)	39.4 (16.3–70.9)	78 (44–111)
	4 100	1973–09	52 670	(30 770–96 970)	56.8 (35.0–89.1)	111 (78–173)
	7 700		40 740	(17 470–82 500)	43.4 (20.1–77.4)	85 (49–141)

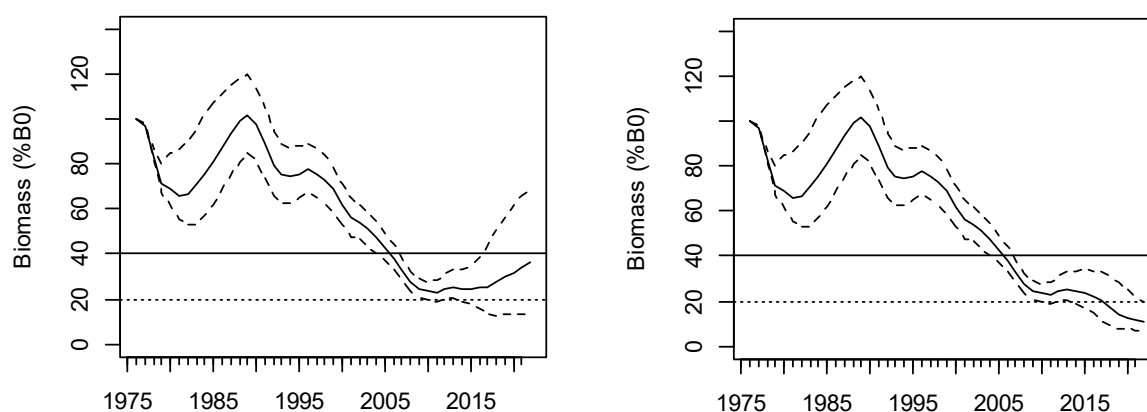


Figure 54: Survey — Estimated median trajectories (with 95% credible intervals shown as dashed lines) for spawning biomass as a percentage of B_0 , projected to 2021 for the best case scenario with future catches assumed to be 4100 t annually and future recruitment sampled from 1973–2009 (left panel) and the worst case scenario with future catches assumed to be 7700 t annually and future recruitment sampled from 2000–2009 (right panel). Horizontal lines show the management target of 40% B_0 and the soft limit of 20% B_0 .

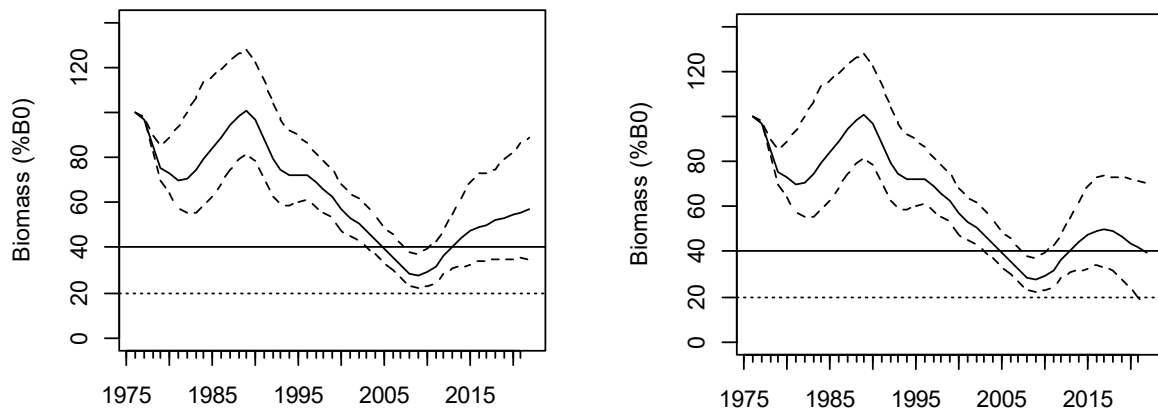


Figure 55: CPUE — Estimated median trajectories (with 95% credible intervals shown as dashed lines) for spawning biomass as a percentage of B_0 , projected to 2021 for the best case scenario with future catches assumed to be 4100 t annually and future recruitment sampled from 1973–2009 (left panel) and the worst case scenario with future catches assumed to be 7700 t annually and future recruitment sampled from 2000–2009 (right panel). Horizontal lines show the management target of 40% B_0 and the soft limit of 20% B_0 .

6.5 Management biomass targets

Probabilities that current and projected spawning biomass would drop below selected management reference points (i.e., target, 40% B_0 ; soft limit, 20% B_0 ; hard limit, 10% B_0) are shown for the survey (Table 19) and CPUE (Table 20) models. The results were strongly influenced by the relative abundance series used, and the assumed future recruitment scenario. When the trawl survey series was used, it appeared unlikely (i.e., about a 10% chance) that B_{2021} would be lower than the soft target of 20% B_0 if current catch levels continued and future recruitment was average, but very likely (i.e., almost an 100% chance) if catches rose to the level of the TACC and recent poor recruitment continued. When the CPUE series was used to inform the biomass trajectory it appeared very unlikely (i.e., less than 6%) that B_{2021} would be lower than the soft target of 20% B_0 under any of the scenarios.

Table 19: Survey model — Probabilities that current (B_{2016}) and projected (B_{2017} – B_{2021}) spawning biomass will be less than 40%, 20% or 10% of B_0 . Projected biomass probabilities are presented for two scenarios of future annual catch (i.e., 4100 t, and 7700 t) and two future recruitment scenarios (YC range).

Future annual catch	YC range	Biomass	Management reference points		
			40% B_0	20% B_0	10% B_0
4 100 t	1973–2009	B_{2016}	0.943	0.229	0
		B_{2017}	0.880	0.197	0.004
		B_{2018}	0.810	0.172	0.005
		B_{2019}	0.727	0.141	0.008
		B_{2020}	0.658	0.116	0.007
		B_{2021}	0.600	0.099	0.006
4 100 t	2000–2009	B_{2016}	0.997	0.577	0.011
		B_{2017}	0.996	0.557	0.029
		B_{2018}	0.994	0.570	0.043
		B_{2019}	0.993	0.581	0.060
		B_{2020}	0.990	0.584	0.082
		B_{2021}	0.988	0.586	0.102
7 700 t	1973–2009	B_{2016}	0.942	0.219	0.004
		B_{2017}	0.912	0.274	0.006
		B_{2018}	0.902	0.346	0.019
		B_{2019}	0.906	0.394	0.030
		B_{2020}	0.908	0.435	0.040
		B_{2021}	0.900	0.450	0.041
7 700 t	2000–2009	B_{2016}	0.997	0.515	0.010
		B_{2017}	0.998	0.677	0.036
		B_{2018}	0.998	0.845	0.124
		B_{2019}	0.999	0.930	0.224
		B_{2020}	1.000	0.950	0.304
		B_{2021}	1.000	0.971	0.362

Table 20: CPUE model — Probabilities that current (B_{2016}) and projected (B_{2017} – B_{2021}) spawning biomass will be less than 40%, 20% or 10% of B_0 . Projected biomass probabilities are presented for two scenarios of future annual catch (i.e., 4100 t, and 7700 t) and two future recruitment scenarios (YC range).

Future annual catch	YC range	Biomass	Management reference points		
			40% B_0	20% B_0	10% B_0
4 100 t	1973–2009	B_{2016}	0.111	0	0
		B_{2017}	0.097	0	0
		B_{2018}	0.083	0	0
		B_{2019}	0.084	0	0
		B_{2020}	0.084	0	0
		B_{2021}	0.072	0	0
4 100 t	2000–2009	B_{2016}	0.119	0	0
		B_{2017}	0.116	0	0
		B_{2018}	0.128	0	0
		B_{2019}	0.149	0	0
		B_{2020}	0.159	0	0
		B_{2021}	0.149	0	0
7 700 t	1973–2009	B_{2016}	0.110	0	0
		B_{2017}	0.141	0	0
		B_{2018}	0.220	0	0
		B_{2019}	0.287	0.002	0
		B_{2020}	0.349	0.009	0
		B_{2021}	0.412	0.025	0
7 700 t	2000–2009	B_{2016}	0.122	0	0
		B_{2017}	0.169	0	0
		B_{2018}	0.271	0.001	0
		B_{2019}	0.366	0.006	0
		B_{2020}	0.448	0.025	0
		B_{2021}	0.515	0.057	0.001

7. DISCUSSION

7.1 Chatham Rise

The base case model estimated that the Chatham Rise spawning stock was currently at about 48% B_0 , and that continued fishing at catch levels around those that have occurred recently was likely to allow the stock to build. If catch levels were to increase four-fold, then stock status was likely to remain relatively constant. All model runs presented were indicative of a current stock status above the management target of 40% B_0 .

The three sensitivity runs examined here all produced estimates of initial and current biomass that were higher than in the base model, and estimates of stock status that were more optimistic. There were, however, no marked differences in the results across all the models.

Information about the stock status of hake on the Chatham Rise appears reasonably strong. Biomass estimates from the Chatham Rise research trawl series strongly suggested a uniform 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. Estimates of year class strengths on the Chatham Rise clearly 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 apparently produced an upturn in the survey estimates of biomass. All model runs produced almost identical patterns of year class strengths.

The series of year class strengths from 1996 to 2013 (excluding 2002, 2010 and 2011) were estimated to be weaker than average. Over the extended series, where year class strengths were based on reasonable quantities of at-age data (i.e., 1984 to 2013), only eight years were above average. For spawning biomass projections, future year class strengths were sampled randomly from those estimated over the 30-year period from 1984 to 2013. Consequently, average year class strengths after 2013 would have continued the generally 'lower than average' trend. If actual year class strengths after 2013 improved on the recent trend then the projected biomasses reported here will be overly pessimistic. Future biomass was also dependent on future catches. Future catch scenarios of 400 t (the average annual catch in the last six years) or 1800 t annually (equal to the HAK 4 TACC) were modelled. All model runs at the higher catch level resulted in little change in future spawning biomass. If the current catch level is maintained, biomass was projected to increase by about 30% over 5 years. It is therefore concluded that biomass in this stock is likely to increase in the future as catches have exceeded 1800 t in only two years since 2001.

Estimates of stock size and projected stock status were influenced by the shape of the selectivity ogives. All ogives were estimated using the double-normal parameterisation. The eastern fishery ogive was essentially logistic in all model runs, but those for the western fishery and the trawl survey varied in shape from logistic to strongly domed. There was no information outside the model that allowed the shape of the estimated selectivity ogives to be verified. The rate of natural mortality (M) was assumed constant in all but the estimate M model, but in reality it is likely to vary with age, being relatively greater for very young and very old fish. Selectivity and natural mortality rate are confounded, as relatively high natural mortality at older ages could be interpreted as relatively low selectivity at those ages.

The median estimate of survey catchability (q) was moderate in the base case assessment (i.e., about 0.16), but both lower and higher in the sensitivity runs (0.08–0.17). These values of median survey q were all within the prior distribution. Hake are believed to be relatively more abundant over rough ground (that would be avoided during a trawl survey), and it is known that hake tend to school off the bottom, particularly during their spring–summer spawning season, hence reducing their availability to the bottom trawl. However, the Chatham Rise trawl survey series does appear to be providing a relatively precise index of relative abundance for this stock. The series declined steadily, but not dramatically, from 1992 to about 2005, and has then shown a slight but variable recovery (which is supported by the appearance of two strong year classes). The CPUE series for the eastern (spawning) fishery does mirror the estimated trawl survey biomass reasonably. The similarity in trends between these two series does suggest (albeit with some circularity) that they are reliable indices of abundance. The CPUE series was incorporated in one of the sensitivity models.

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. 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. 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.

The assessment for Chatham Rise hake has been updated, and was indicative of a stock that has been steadily fished down throughout the 1990s, but that it was likely to be above the management target of 40% B_0 set for this species. Recruitment of the strong 2002 and 2011 year classes had apparently

stopped the stock decline, and future annual catches of around the recent average (i.e., 400 t) would be likely to result in further stock rebuilding over the next five years (see Table 15). It was likely that the stock was being reasonably well monitored by the January trawl survey series. There were probably no sustainability issues for this hake stock, but continued monitoring is important as any increase in catches or continued poor spawning success could drive the spawning biomass towards the soft limit of 20% B_0 .

7.2 West coast South Island

Most previous assessments of the HAK 7 (west coast South Island) stock have been problematic because there were no reliable indices of relative abundance (Dunn 2004a, Horn 2011). While CPUE series have been produced previously (e.g., Ballara & Horn 2011) the trends in these series have generally not been plausible, and it was concluded that catch rates of hake off WCSI were influenced more by fisher behaviour than by abundance of the species. Consequently, using the available CPUE series in the model would probably be misleading (Horn 2011). Several ‘one-off’ research surveys of hoki and hake have been conducted by different vessels off WCSI, but these provide no useful relative biomass series. A long-running trawl survey series of inshore waters off WCSI by *Kaharoa* does not provide a useful index of hake biomass as it surveys no deeper than 400 m (Stevenson & Hanchet 2000). Consequently, a HAK 7 assessment by Horn (2011) included only biological parameters, a catch history, and proportion-at-age data from the commercial fishery since 1990 and the *Wesermünde* survey in 1979. While catch-at-age data can provide information on exploitation rate and therefore biomass, they are likely to be much more informative when tuned using a relative abundance series. The HAK 7 assessment by Horn (2011) was considered too unreliable to be reported in the 2011 Plenary Document.

A subsequent assessment (Horn 2013b) differed significantly from the 2011 assessment in two respects. First, it included a CPUE series that was considered by the Deepwater Fisheries Assessment Working Group to be reliable. That series commenced when the deemed value scheme was introduced (2001), and so was believed to be less biased by changes in fishing practice and catch reporting behaviour that had confounded longer CPUE series. Second, the assessment included two comparable trawl biomass indices from surveys that had covered a large proportion of the likely hake habitat off WCSI. The base case model indicated that the WCSI spawning stock was at about 58% B_0 , and that continued fishing at recent catch levels was likely to allow stock size to increase slowly. That assessment was accepted by the Working Group, the first time this had occurred since 2004.

Since the assessment by Horn (2013b), two additional points have been added to the research survey series. It is now apparent, however, that there is a conflict between the two relative abundance indices. The trawl survey indicated a recent declining biomass with current biomass being lower than in 2000, whereas the CPUE indicated a recent increase in biomass and a current level similar to that in 2000. The Working Group was unable to determine which of the two series was most likely to index the biomass of the stock, as both had known drawbacks. The trawl survey series was still relatively sparse and it did not survey the entire area off WCSI where hake are known to be relatively abundant. The CPUE series had already been truncated (at 2001) because earlier data were considered unreliable and biased (Ballara 2013), but there may still be biases in the series since 2001 relating to changes in fishing technology and in the commercial (economic) desirability of hake that are not captured in the QMS effort statistics, and so cannot be standardised for in any CPUE model. Consequently, results from the two models (Survey, and CPUE) were reported in the 2017 Plenary Document.

The survey model indicated that the WCSI spawning stock was at about 26% B_0 , and that continued fishing at recent catch levels was likely to allow stock size to increase slowly, but only if some future recruited year classes are stronger than the average since 2000. An increase in catch levels was likely to cause the stock to decline further. It is possible that the 2014 year class was relatively strong, based on the results of estimated proportion-at-age data from the 2016 research survey (O’Driscoll & Ballara 2017). However, it will be another 2–4 years before data from the fishery indicates whether or not this year class will contribute significantly to stock biomass. In contrast to the survey model, the CPUE

model indicated that current stock status was about 50% B_0 , and that at current or increased landings levels the stock biomass in 2012 had a low probability (i.e., less than a 6% chance) of being lower than 20% B_0 , even if future recruitment remains as poor as it has been since about 2000.

Estimated year class strengths often had quite wide 95% bounds, particularly at the start and the end of the estimated series. However, the median estimates suggested that variation in year class strength was not great for this stock; only four (survey model) or two (CPUE model) of the estimates from 1973 to 2009 were outside the range 0.5–2. A greater level of year class strength variation, but still relatively low, was also estimated for the hake stock on the Chatham Rise. However, it was not possible to tell whether the low variability in hake year class strengths was correct (i.e., the actual variability is low) or a consequence of uninformative data (e.g., the year-class signal in the observer data could be poor, either because these data were not representative of the population, or because it is masked by year-to-year variation in selectivity).

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. The projected stock status relies on adequate estimation of recent year class strengths and recruitment. The commercial catch proportions-at-age distributions (which drive the year class strength estimates) are not collected systematically over time or space. Although the stratification used in the analyses of these data coupled with the removal of sex from the partition is believed to produce reasonable estimates of catch-at-age for the fishery, the projections of future stock status based on these data are likely to underestimate the true level of uncertainty.

The assessment for WCSI hake has been updated, and was indicative of a stock that was steadily fished down for 20 years from about 1990. However, unlike in the last published assessment for this stock (Horn 2013a), the current stock status and the likely biomass trajectory since 2010 were very uncertain. The two relative abundance series used in this assessment indicated markedly different levels of virgin spawning biomass (i.e., 92 000 t for CPUE, and 79 000 t for the trawl survey). The fishery catch-at-age data indicated a B_0 in the middle of that range. The two relative abundance series also indicated markedly different trends in recent biomass. Consequently, there were two conflicting assessment models available for consideration, one implying no sustainability issues, and the other indicating that the stock will more likely than not be below 20% B_0 by 2021. Improved confidence in the assessment of this hake stock will hopefully be achieved as the winter research survey series continues. In the interim, however, there is a clear need to try to determine which of the two relative abundance series is most accurate, and therefore, which of the two assessment scenarios should be used to inform the management of hake off WCSI.

8. ACKNOWLEDGMENTS

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APPENDIX A: RESOURCE SURVEY BIOMASS INDICES FOR HAKE IN HAK 1, HAK 4 AND HAK 7

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

Vessel	Date	Trip code	Depth	Biomass	CV	Reference
<i>Wesermünde</i>	Mar–May 1979		— ¹	—	—	Kerstan & Sahrhage 1980
<i>Wesermünde</i>	Oct–Dec 1979		— ¹	—	—	Kerstan & Sahrhage 1980
<i>Shinkai Maru</i>	Mar–Apr 1982	SHI8201	200–800	6 045	0.15	N.W. Bagley, NIWA, pers. comm.
<i>Shinkai Maru</i>	Oct–Nov 1983	SHI8303	200–800	11 282	0.22	N.W. Bagley, NIWA, pers. comm.
<i>Amaltal Explorer</i>	Oct–Nov 1989	AEX8902	200–800	2 660	0.21	Livingston & Schofield 1993
<i>Amaltal Explorer</i>	Jul–Aug 1990	AEX9001	300–800	4 343	0.19	Hurst & Schofield 1995
<i>Amaltal Explorer</i>	Nov–Dec 1990	AEX9002	300–800	2 460	0.16	N.W. Bagley, NIWA, pers. comm.
<i>Tangaroa</i>	Nov–Dec 1991	TAN9105	Reported ²	5 686	0.43	Chatterton & Hanchet 1994
			300–800 ³	5 553	0.44	O'Driscoll & Bagley 2001
			1991 area ⁴	5 686	0.43	O'Driscoll & Bagley 2001
			1996 area ⁵	—	—	
<i>Tangaroa</i>	Apr–May 1992	TAN9204	Reported ²	5 028	0.15	Schofield & Livingston 1994a
			300–800 ³	5 028	0.15	O'Driscoll & Bagley 2001
			1991 area ⁴	—	—	
			1996 area ⁵	—	—	
<i>Tangaroa</i>	Sep–Oct 1992	TAN9209	Reported ²	3 762	0.15	Schofield & Livingston 1994b
			300–800 ^{3,7}	3 760	0.15	O'Driscoll & Bagley 2001
			1991 area ⁴	—	—	
			1996 area ⁵	—	—	
<i>Tangaroa</i>	Nov–Dec 1992	TAN9211	Reported ²	1 944	0.12	Ingerson et al. 1995
			300–800 ³	1 822	0.12	O'Driscoll & Bagley 2001
			1991 area ⁴	1 944	0.12	O'Driscoll & Bagley 2001
			1996 area ⁵	—	—	
<i>Tangaroa</i>	May–Jun 1993	TAN9304 ⁶	Reported ²	3 602	0.14	Schofield & Livingston 1994c
			300–800 ³	3 221	0.14	O'Driscoll & Bagley 2001
			1991 area ⁴	—	—	
			1996 area ⁵	—	—	

Table A1 ctd.

Vessel	Date	Trip code	Depth	Biomass	CV	Reference
<i>Tangaroa</i>	Nov–Dec 1993	TAN9310	Reported ²	2 572	0.12	Ingerson & Hanchet 1995
			300–800 ³	2 286	0.12	O'Driscoll & Bagley 2001
			1991 area ⁴	2 567	0.12	O'Driscoll & Bagley 2001
			1996 area ⁵	—	—	
<i>Tangaroa</i>	Mar–Apr 1996	TAN9605	Reported ²	3 946	0.16	Colman 1996
			300–800 ³	2 026	0.12	O'Driscoll & Bagley 2001
			1991 area ⁴	2 281	0.17	O'Driscoll & Bagley 2001
			1996 area ⁵	2 825	0.12	O'Driscoll & Bagley 2001
<i>Tangaroa</i>	Apr–May 1998	TAN9805	Reported ²	2 554	0.18	Bagley & McMillan 1999
			300–800 ³	2 554	0.18	O'Driscoll & Bagley 2001
			1991 area ⁴	2 643	0.17	O'Driscoll & Bagley 2001
			1996 area ⁵	3 898	0.16	O'Driscoll & Bagley 2001
<i>Tangaroa</i>	Nov–Dec 2000	TAN0012	300–800 ³	2 194	0.17	O'Driscoll et al. 2002
			1991 area ⁴	2 657	0.16	O'Driscoll et al. 2002
			1996 area ⁵	3 103	0.14	O'Driscoll et al. 2002
<i>Tangaroa</i>	Nov–Dec 2001	TAN0118	300–800 ³	1 831	0.24	O'Driscoll & Bagley 2003a
			1991 area ⁴	2 170	0.20	O'Driscoll & Bagley 2003a
			1996 area ⁵	2 360	0.19	O'Driscoll & Bagley 2003a
<i>Tangaroa</i>	Nov–Dec 2002	TAN0219	300–800 ³	1 283	0.20	O'Driscoll & Bagley 2003b
			1991 area ⁴	1 777	0.16	O'Driscoll & Bagley 2003b
			1996 area ⁵	2 037	0.16	O'Driscoll & Bagley 2003b
<i>Tangaroa</i>	Nov–Dec 2003	TAN0317	300–800 ³	1 335	0.24	O'Driscoll & Bagley 2004
			1991 area ⁴	1 672	0.23	O'Driscoll & Bagley 2004
			1996 area ⁷	1 898	0.21	O'Driscoll & Bagley 2004
<i>Tangaroa</i>	Nov–Dec 2004	TAN0414	300–800 ³	1 250	0.27	O'Driscoll & Bagley 2006a
			1991 area ⁴	1 694	0.21	O'Driscoll & Bagley 2006a
			1996 area ⁷	1 774	0.20	O'Driscoll & Bagley 2006a
<i>Tangaroa</i>	Nov–Dec 2005	TAN0515	300–800 ³	1 133	0.20	O'Driscoll & Bagley 2006b
			1991 area ⁴	1 459	0.17	O'Driscoll & Bagley 2006b
			1996 area ⁷	1 624	0.17	O'Driscoll & Bagley 2006b

Table A1 ctd.

Vessel	Date	Trip code	Depth	Biomass	CV	Reference
<i>Tangaroa</i>	Nov–Dec 2006	TAN0617	300–800 ³	998	0.22	O'Driscoll & Bagley 2008
			1991 area ⁴	1 530	0.17	O'Driscoll & Bagley 2008
			1996 area ⁷	1 588	0.16	O'Driscoll & Bagley 2008
<i>Tangaroa</i>	Nov–Dec 2007	TAN0714	300–800 ³	2 188	0.17	Bagley et al. 2009
			1991 area ⁴	2 470	0.15	Bagley et al. 2009
			1996 area ⁷	2 622	0.15	Bagley et al. 2009
<i>Tangaroa</i>	Nov–Dec 2008	TAN0813	300–800 ³	1 074	0.23	O'Driscoll & Bagley 2009
			1991 area ⁴	2 162	0.17	O'Driscoll & Bagley 2009
			1996 area ⁷	2 355	0.16	O'Driscoll & Bagley 2009
<i>Tangaroa</i>	Nov–Dec 2009	TAN0911	300–800 ³	992	0.22	Bagley & O'Driscoll 2012
			1991 area ⁴	1 442	0.20	Bagley & O'Driscoll 2012
			1996 area ⁷	1 602	0.18	Bagley & O'Driscoll 2012
<i>Tangaroa</i>	Nov–Dec 2011	TAN1117	300–800 ³	1 434	0.30	Bagley et al. 2013
			1991 area ⁴	1 885	0.24	Bagley et al. 2013
			1996 area ⁷	2 004	0.23	Bagley et al. 2013
<i>Tangaroa</i>	Nov–Dec 2012	TAN1215	300–800 ³	1 943	0.23	Bagley et al. 2014
			1991 area ⁴	2 428	0.23	Bagley et al. 2014
			1996 area ⁷	2 443	0.22	Bagley et al. 2014
<i>Tangaroa</i>	Nov–Dec 2014	TAN1412	300–800 ³	1 101	0.32	Bagley et al. 2016
			1991 area ⁴	1 477	0.25	Bagley et al. 2016
			1996 area ⁷	1 485	0.25	Bagley et al. 2016
<i>Tangaroa</i>	Nov–Dec 2016	TAN1614	300–800 ³	1 000	0.25	R. O'Driscoll, NIWA, unpublished data
			1991 area ⁴	–	–	R. O'Driscoll, NIWA, unpublished data
			1996 area ⁷	–	–	R. O'Driscoll, NIWA, unpublished data

1. Although surveys by *Wesermünde* were carried out in the Sub-Antarctic in 1979, biomass estimates for hake were not calculated.
2. The depth range, biomass and CV in the original report.
3. The biomass and CV calculated from source records using the equivalent 1991 region, but excluding both the 800–1000 m strata in Puysegur region and the Bounty Platform strata.
4. The biomass and CV calculated from source records using the equivalent 1991 region, which includes the 800–1000 m strata in Puysegur region but excludes the Bounty Platform strata.
5. The biomass and CV calculated from source records using the equivalent 1996 region, which includes the 800–1000 m strata in Puysegur region but excludes the Bounty Platform strata. (The 1996 region added additional 800–1000 m strata to the north and to the south of the Sub-Antarctic to the 1991 region).
6. Doorspread data not recorded for this survey. Analysis of source data with average of all other survey doorspread estimates resulted in a new estimate of biomass.
7. The biomass and CV calculated from source records using the equivalent 1996 region, which includes the 800–1000 m strata in Puysegur region but excludes the Bounty Platform strata. (The 1996 region added additional 800–1000 m strata to the north and to the south of the Sub-Antarctic to the 1991 region). However, in 2003, stratum 26 (the most southern 800–1000 m strata) was not surveyed. In previous years this stratum yielded either a very low or zero hake biomass. The yield in 2003 from stratum 26 was assumed to be zero.

Table A2: 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	Date	Trip code	Depth	Biomass	CV	Reference
<i>Wesermünde</i>	Mar–May 1979		– ¹	–	–	Kerstan & Sahrhage 1980
<i>Wesermünde</i>	Oct–Dec 1979		– ¹	–	–	Kerstan & Sahrhage 1980
<i>Shinkai Maru</i>	Mar 1983	SHI8301	200–800	11 327	0.12	N.W. Bagley, NIWA, pers. comm.
<i>Shinkai Maru</i>	Nov–Dec 1983	SHI8304	200–800 ²	8 160	0.12	N.W. Bagley, NIWA, pers. comm.
<i>Shinkai Maru</i>	Jul 1986	SHI8602	200–800	7 630	0.13	N.W. Bagley, NIWA, pers. comm.
<i>Amaltal Explorer</i>	Nov–Dec 1989	AEX8903	200–800	3 576	0.19	N.W. Bagley, NIWA, pers. comm.
<i>Tangaroa</i>	Jan 1992	TAN9106	200–800	4 180	0.15	Horn 1994a
<i>Tangaroa</i>	Jan 1993	TAN9212	200–800	2 950	0.17	Horn 1994b
<i>Tangaroa</i>	Jan 1994	TAN9401	200–800	3 353	0.10	Schofield & Horn 1994
<i>Tangaroa</i>	Jan 1995	TAN9501	200–800	3 303	0.23	Schofield & Livingston 1995
<i>Tangaroa</i>	Jan 1996	TAN9601	200–800	2 457	0.13	Schofield & Livingston 1996
<i>Tangaroa</i>	Jan 1997	TAN9701	200–800	2 811	0.17	Schofield & Livingston 1997
<i>Tangaroa</i>	Jan 1998	TAN9801	200–800	2 873	0.18	Bagley & Hurst 1998
<i>Tangaroa</i>	Jan 1999	TAN9901	200–800	2 302	0.12	Bagley & Livingston 2000
<i>Tangaroa</i>	Jan 2000	TAN0001	200–800	2 090	0.09	Stevens et al. 2001
			200–1000	2 152	0.09	Stevens et al. 2001
<i>Tangaroa</i>	Jan 2001	TAN0101	200–800	1 589	0.13	Stevens et al. 2002
<i>Tangaroa</i>	Jan 2002	TAN0201	200–800	1 567	0.15	Stevens & Livingston 2003
			200–1000	1 905	0.13	Stevens & Livingston 2003
<i>Tangaroa</i>	Jan 2003	TAN0301	200–800	888	0.16	Livingston et al. 2004
<i>Tangaroa</i>	Jan 2004	TAN0401	200–800	1 547	0.17	Livingston & Stevens 2005
<i>Tangaroa</i>	Jan 2005	TAN0501	200–800	1 048	0.18	Stevens & O'Driscoll 2006
<i>Tangaroa</i>	Jan 2006	TAN0601	200–800	1 384	0.19	Stevens & O'Driscoll 2007
<i>Tangaroa</i>	Jan 2007	TAN0701	200–800	1 824	0.12	Stevens et al. 2008
			200–1000	1 976	0.12	Stevens et al. 2008
<i>Tangaroa</i>	Jan 2008	TAN0801	200–800	1 257	0.13	Stevens et al. 2009a
			200–1000	1 323	0.13	Stevens et al. 2009a
<i>Tangaroa</i>	Jan 2009	TAN0901	200–800	2 419	0.21	Stevens et al. 2009b
<i>Tangaroa</i>	Jan 2010	TAN1001	200–800	1 701	0.25	Stevens et al. 2011
			200–1300	1 862	0.25	Stevens et al. 2011

Table A2 ctd.

<i>Tangaroa</i>	Jan 2011	TAN1101	200–800	1 099	0.15	Stevens et al. 2012
			200–1300	1 201	0.14	Stevens et al. 2012
<i>Tangaroa</i>	Jan 2012	TAN1201	200–800	1 292	0.15	Stevens et al. 2013
			200–1300	1 493	0.13	Stevens et al. 2013
<i>Tangaroa</i>	Jan 2013	TAN1301	200–800	1 793	0.15	Stevens et al. 2014
			200–1300	1 874	0.15	Stevens et al. 2014
<i>Tangaroa</i>	Jan 2014	TAN1401	200–800	1 377	0.15	Stevens et al. 2015
			200–1300	1 510	0.14	Stevens et al. 2015
<i>Tangaroa</i>	Jan 2016	TAN1601	200–800	1 299	0.19	Stevens et al. 2017
			200–1300	1 512	0.16	Stevens et al. 2017

1. Although surveys by *Wesermünde* were carried out on the Chatham Rise in 1979, biomass estimates for hake were not calculated.

2. East of 176° E only.

Table A3: Biomass indices (t) and coefficients of variation (CV) for hake from comparable resource surveys off WCSI. (These estimates assume that the areal availability, vertical availability, and vulnerability are equal to one.)

Vessel	Date	Trip code	Depth	Biomass	CV	Reference
<i>Tangaroa</i>	Jul–Aug 2000	TAN0007	300–650	803	0.13	O’Driscoll & Ballara 2017
<i>Tangaroa</i>	Jul–Aug 2012	TAN1210	300–650	583	0.13	O’Driscoll & Ballara 2017
			200–800	1 103	0.13	O’Driscoll & Ballara 2017
<i>Tangaroa</i>	Jul–Aug 2013	TAN1308	300–650	331	0.17	O’Driscoll & Ballara 2017
			200–800	747	0.21	O’Driscoll & Ballara 2017
<i>Tangaroa</i>	Jul–Aug 2016	TAN1609	300–650	221	0.24	O’Driscoll & Ballara 2017
			200–800	355	0.16	O’Driscoll & Ballara 2017
			200–1000	502	0.13	O’Driscoll & Ballara 2017

APPENDIX B: COMPARISON OF MODEL RESULTS – CASAL VS. CASAL2

The general-purpose stock assessment program CASAL v2.30 (Bull et al. 2012) is in the process of being redeveloped as “Casal2”. The new version will be easier to maintain and modify, will have wider applications and more modelling options than CASAL, and will allow the input of data series not currently able to be used in CASAL. However, when shifting between assessment programs that are intended to behave in the same way, it is essential to ensure that the same results are produced when using identical input data. To check this, the base case model for the HAK 4 assessment presented above was configured and run in Casal2.

Outputs from MPD runs from CASAL and Casal2 are presented in Table B1 and showed there to be no differences out to at least four significant figures.

Table B1: MPD output from CASAL and Casal2 runs using identical data, with differences shown in red.

	CASAL	Casal2	Difference			CASAL	Casal2				CASAL	Casal2	
B0	40539.4	40539	0.4	year	true_YCS	true_YCS	Difference	year	SSB	SSB	Difference		
chatTANq	0.0965648	0.0965666	-1.8E-06	1975	1.50706	1.50705	1E-05	1975	40463.2	40462.8	0.4		
				1976	1.53433	1.53432	1E-05	1976	40185.8	40185.4	0.4		
Selectivity				1977	1.5572	1.55719	1E-05	1977	39458.9	39458.5	0.4		
TAN	14.5003	14.5005	-0.0002	1978	1.57556	1.57554	2E-05	1978	39014.6	39014.2	0.4		
	8.48529	8.48539	-1E-04	1979	1.58854	1.58852	2E-05	1979	39105.1	39104.8	0.3		
	5.57322	5.57319	3E-05	1980	1.59036	1.59034	2E-05	1980	39326.2	39325.8	0.4		
OBswest	6.97053	6.9705	3E-05	1981	1.57531	1.57529	2E-05	1981	39990.8	39990.4	0.4		
	3.38162	3.38163	-1E-05	1982	1.55396	1.55394	2E-05	1982	41171.4	41170.9	0.5		
	8.25739	8.2577	-0.00031	1983	1.54124	1.54122	2E-05	1983	42899.6	42899.1	0.5		
OBSeast	10.9075	10.9077	-0.0002	1984	0.798198	0.798205	-7E-06	1984	44888.4	44887.8	0.6		
	3.77949	3.77955	-6E-05	1985	0.823995	0.823983	1.2E-05	1985	46776	46775.3	0.7		
	7.6594	7.6593	1E-04	1986	0.939351	0.939327	2.4E-05	1986	48529.8	48529	0.8		
				1987	0.680324	0.680373	-4.9E-05	1987	50053.3	50052.4	0.9		
Objective function				1988	0.962622	0.96258	4.2E-05	1988	51048.4	51047.5	0.9		
Total	763.95	763.653	0.297	1989	0.800118	0.800124	-6E-06	1989	51182.5	51181.6	0.9		
chatTANbiomass	-22.9612	-22.961076	-0.000124	1990	1.21852	1.21854	-2E-05	1990	50266.7	50265.7	1		
chatTANage	382.09	382.0904	-0.0004	1991	1.79638	1.79639	-1E-05	1991	48587.5	48586.5	1		
chatOBSeast	153.145	153.1453	-0.0003	1992	1.37032	1.37033	-1E-05	1992	46173	46172.1	0.9		
chatOBSwst	247.312	247.31175	0.00025	1993	1.15785	1.15785	0	1993	42926	42925.1	0.9		
prior_on_initialization.B0	10.61	10.61	0	1994	1.08435	1.08436	-1E-05	1994	39340.6	39339.8	0.8		
prior_on_recruitment.YCS	-13.1634	-13.46059	0.29719	1995	0.866262	0.86626	2E-06	1995	36153	36152.3	0.7		
prior_on_q_chatTAN	-2.26651	-2.2665	-1E-05	1996	0.570124	0.570132	-8E-06	1996	33839.5	33838.8	0.7		
YCS_average_1	9.02344	9.02324	0.0002	1997	0.537035	0.537033	2E-06	1997	32473.8	32473.2	0.6		
smoothYCS	0.160856	0.160845	1.1E-05	1998	0.372399	0.372407	-8E-06	1998	31903.5	31902.9	0.6		
				1999	0.577239	0.577232	7E-06	1999	30602	30601.5	0.5		
				2000	0.372495	0.372502	-7E-06	2000	28465	28464.5	0.5		