Ministry for Primary Industries
Manatū Ahu Matua

Stock assessment of hake (*Merluccius australis*) in the Sub-Antarctic (part of HAK 1) for the 2014–15 fishing year

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EXECUTIVE SUMMARY

This report summarises the stock assessment of hake in Quota Management Area HAK 1 south of latitude 46° S (the Sub-Antarctic) for the 2014–15 fishing year. An updated Bayesian assessment was conducted using the general-purpose stock assessment program CASAL v2.30. The assessment incorporated all relevant biological parameters, the commercial catch histories, updated trawl fishery CPUE series, and series of proportion-at-age data from the commercial trawl fishery and two research survey series. The analysis includes fishery data up to the end of the 2012–13 fishing year

The previous assessment had removed sex from the model partition to alleviate problems caused by inconsistencies in sex ratios in the at-age data. This is not an ideal solution, however, because there are marked differences in growth between sexes, so initial investigations here looked at returning sex to the partition. It was established that sex in or out of the partition, and sexed or unsexed selectivity, had little impact on biomass or stock status. However, when selectivity was estimated by sex, the ogives varied markedly between sexes and so were unrealistic, and models with sexed observations exhibited trends in the fits to these data. The model that best avoided undesirable fitting trends and produced the most believable selectivity ogives and trawl survey catchabilities was one with sex in the partition, but with unsexed observations, unsexed selectivity, and estimation of age-dependent M. Impacts on this base model of down-weighting the catch-at-age data, fixing M, estimating M as a constant rather than an age-dependent ogive, and including the trawl fishery CPUE series were also investigated.

The stock status of hake in the Sub-Antarctic is not well known in absolute terms. It appears likely that the stock has declined throughout the 1990s, with the decline driven by poor recruitment rather than fishing pressure. The base model estimated that the Sub-Antarctic spawning stock is currently at about 60% B_0, and that B_0 was about 59 000 t. Continued fishing at recent catch levels (about 2000 t annually) is likely to allow stock size to increase slightly in the next five years. Sensitivity model runs down-weighting the at-age data or varying M did not markedly alter the estimate of stock status (i.e., estimates ranged from 55 to 68% B_0). A sensitivity run including a trawl fishery CPUE series did indicate a higher level of absolute biomass and a much more optimistic current stock status. However, none of the model runs were indicative of current biomass being lower than 37% of B_0 (i.e., the most pessimistic 95% credible interval lower bound).

The stock is probably being well monitored by the November-December trawl survey series. While the stock status appears to be reasonably well defined, estimates of past and current absolute stock size are very uncertain due to little contrast in the relative abundance series. However, there are probably no current sustainability issues for this stock.

1. INTRODUCTION

This report outlines the stock assessment of hake (*Merluccius australis*) in the Sub-Antarctic section of Quota Management Area (QMA) HAK 1 (i.e., HAK 1 south of latitude 46° S), with the inclusion of data up to the end of the 2012–13 fishing year. The current stock hypothesis for New Zealand hake suggests that there are three separate hake stocks (Colman 1998); the west coast South Island stock (WCSI, the area of HAK 7 off the west coast of South Island), the Sub-Antarctic stock (the area of HAK 1 that encompasses the Southern Plateau, the Stewart-Snares shelf, and Puysegur Bank), and the Chatham Rise stock (HAK 4 and the area of HAK 1 on the western Chatham Rise).

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

This report fulfils Objective 1 of Project DEE2010-02HAKC "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.

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 (0+) are found in shallower inshore regions under 250 m (Hurst et al. 2000). Hake are taken by large trawlers — often as bycatch in fisheries targeting other species such as hoki and southern blue whiting, although target fisheries also exist (Devine 2009). Present management divides the fishery into three main fish stocks: (a) the Challenger QMA (HAK 7), (b) the Southeast (Chatham Rise) QMA (HAK 4), and (c) the remainder of the EEZ comprising the Auckland, Central, Southeast (Coast), Southland, and Sub-Antarctic QMAs (HAK 1). An administrative fish stock exists in the Kermadec QMA (HAK 10) although there are no recorded landings from this area. The hake QMAs are shown in Figure 1.

The largest fishery 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. Currently, the TACC for HAK 7 is the largest, at 7700 t out of a total for the EEZ of 13 211 t. The WCSI hake fishery has generally consisted of bycatch in the much larger hoki fishery, but it has undergone a number of changes during the last decade (Ballara 2015). 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 there has been a hake target fishery in September after the peak of the hoki fishery is over (Ballara 2015).

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 (Devine 2009, Ballara 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 since. 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 is believed to be sustainable in the short term.

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 (Devine 2009, Ballara 2015).
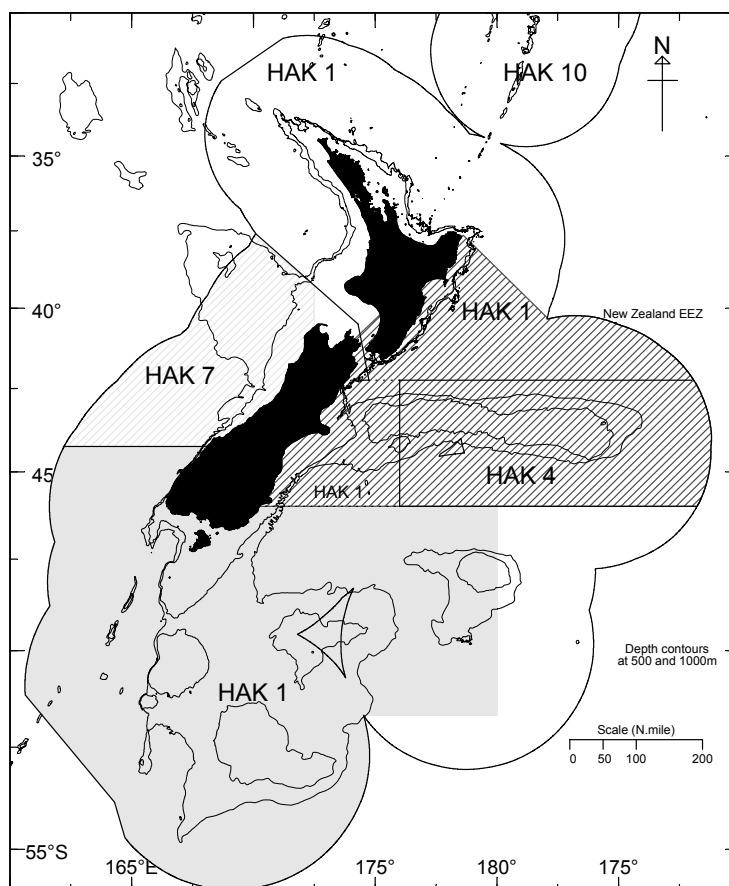

Figure 1: Quota Management Areas (QMAs) HAK 1, 4, 7, & 10; and the west coast South Island (light shading), Chatham Rise (dark shading), and Sub-Antarctic (medium shading) hake stock boundaries assumed in this report.

1.2   Assessment 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), and 2010–11 (Horn 2011). The most recent assessments by stock are: Sub-Antarctic for 2011–12 (Horn 2013a), and Chatham Rise and WCSI for 2012–13 (Horn 2013b). The Bayesian stock assessment software CASAL (Bull et al. 2012) has been used for all assessments since 2002–03.

Standardised CPUE indices for the WCSI and Chatham Rise stocks were updated to the 2011–12 fishing year by Ballara (2013), and for the Sub-Antarctic stock to the 2012–13 fishing year by Ballara (2015). The latter document also included a descriptive analysis of all New Zealand's hake fisheries up to the 2012–13 fishing year.

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 2012–13 (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 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. The catch from the most recent year was assumed based on landings from previous years.

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

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 2012–13 and actual TACCs (t) for 1986–87 to 2012–13. Data from 1983–84 to 1985–86 from Fisheries Statistics Unit; data from 1986–87 to 2012–13 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	5 837	13 211
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

Table 3: Revised landings (t) by QMA 1989–90 to 2012–13 from Ballara (2015).

Fishing Year	HAK 1	HAK 4	QMA HAK 7	Total
1989–90	2 115	763	4 903	7 781
1990–91	2 593	726	6 175	9 494
1991–92	3 156	2 013	3 027	8 196
1992–93	3 522	2 546	7 157	13 225
1993–94	1 787	2 587	2 990	7 364
1994–95	2 346	2 896	9 538	14 780
1995–96	3 828	3 070	9 089	15 987
1996–97	3 300	3 190	6 846	13 336
1997–98	3 659	3 239	7 683	14 581
1998–99	3 703	2 740	8 786	15 229
1999–00	3 781	2 756	7 042	13 579
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

Table 4: Revised landings (t) from 1974–75 to 2013–14 for the Sub-Antarctic (Sub-A), Chatham Rise (Chat), and west coast South Island (WCSI) stocks. The landing from the most recent year is assumed based on recent trends in the fishery.

Fishing year	Sub-A	Chat	WCSI	Fishing year	Sub-A	Chat	WCSI
1974–75	120	191	71	1994–95	1 852	3 271	9 535
1975–76	281	488	5 005	1995–96	2 873	3 959	9 082
1976–77	372	1 288	17 806	1996–97	2 262	3 890	6 838
1977–78	762	34	498	1997–98	2 606	4 074	7 674
1978–79	364	609	4 737	1998–99	2 796	3 589	8 742
1979–80	350	750	3 600	1999–00	3 020	3 174	7 031
1980–81	272	997	2 565	2000–01	2 790	2 962	8 346
1981–82	179	596	1 625	2001–02	2 510	1 770	7 498
1982–83	448	302	745	2002–03	2 738	1 401	7 404
1983–84	722	344	945	2003–04	3 245	2 465	7 939
1984–85	525	544	965	2004–05	2 531	3 518	7 298
1985–86	818	362	1 918	2005–06	2 557	489	6 892
1986–87	713	509	3 755	2006–07	1 818	1 081	7 660
1987–88	1 095	574	3 009	2007–08	2 202	1 096	2 583
1988–89	1 237	804	8 696	2008–09	2 427	1 825	5 912
1989–90	1 927	950	8 741	2009–10	1 958	391	2 282
1990–91	2 370	931	8 246	2010–11	1 288	951	3 462
1991–92	2 750	2 418	3 010	2011–12	1 892	194	4 299
1992–93	3 269	2 798	7 059	2012–13	1 863	344	5 171
1993–94	1 453	2 934	2 971	2013–14	1 800	–	–

2.2 Other sources of fishing mortality

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. 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 RESOURCE SURVEYS

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. 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 (2014).

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 stock 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 trawl survey samples with 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, with maturity 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 ≥ 0.005 (males) or GSI ≥ 0.015 (females). Fish identified as stages 3–7 were classified as mature. From 2009 to 2011, fixed ogives as derived from the previously described model fitting procedure were used in the assessment models. In 2012, fixed ogives for all stocks were updated by fitting a logistic curve (from Bull et al. 2012) to the proportion mature at age data, by sex, with the fish classified as mature or immature as described above. 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 sex 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 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, juvenile hake have been taken in coastal waters on both sides of the South Island and on the Campbell Plateau. It is known that they 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 (M) and the associated methodology were given by Dunn et al. (2000); M was estimated as 0.18 y^{-1} for females and 0.20 y^{-1} for males. Colman et al. (1991) estimated M as 0.20 y^{-1} for females and 0.22 y^{-1} for males using the maximum age method of Hoenig (1983) (where they defined the maximum ages at which 1% of the population survives in an unexploited stock as 23 years for females and 21 years for males). These are similar to the values proposed by Horn (1997), who determined the age of hake by counting zones in sectioned otoliths and concluded from that study that it was likely that M was in the range 0.20–0.25 y^{-1}. Up to 2011, constant values of M were used in stock assessment models. However, because true M is likely to vary with age, and there is a considerable volume of catch-at-age data available for this stock, most of the MCMC assessments presented below estimate an ogive for M within the models.

A steepness parameter (h) of 0.9 for the Beverton and Holt stock-recruitment relationship was used in hake assessments up to 2012. There are no estimates of this parameter for *M. australis*. However, reported estimates of h by Rose et al. (2001) for other *Merluccius* species ranged from 0.70 to 0.87, and a mean estimated value for Gadidae (including some *Merluccius* species) of 0.79 was reported by Myers et al. (1999). Consequently, since 2014, assessments of *M. australis* have used an h of 0.8.

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.

Length-weight relationships for hake from all three stocks were revised by Horn (2013a, 2013b) using all available length-weight data collected during trawl surveys since 1989.
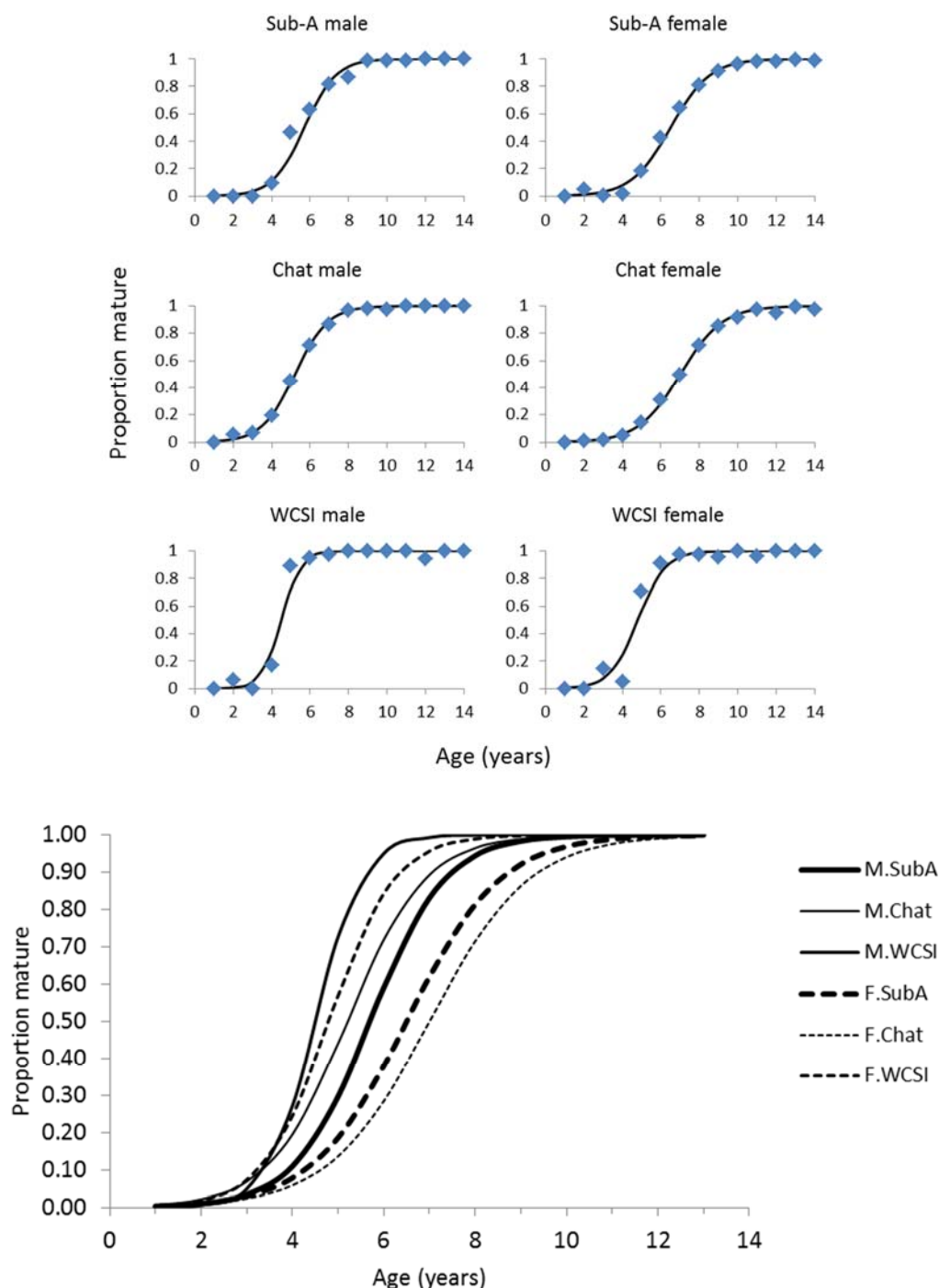

Figure 2: Raw proportion mature at age data with fitted logistic ogives (upper panel), and a comparison plot (lower panel) of all estimated ogives by stock for male (M, solid lines) and female (F, broken lines) hake.

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

		Estimate	Source

Natural mortality

Males	$M = 0.20$		(Dunn et al. 2000)
Females	$M = 0.18$		(Dunn et al. 2000)

Weight = a·(length)^b (Weight in t, length in cm)

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 2013b)
Females	$a = 1.88 \times 10^{-9}$	$b = 3.305$		(Horn 2013b)
Both sexes	$a = 2.00 \times 10^{-9}$	$b = 3.288$		(Horn 2013b)

von Bertalanffy growth parameters

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)

Schnute growth parameters ($\tau_1 = 1$ and $\tau_2 = 20$ for all stocks)

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)

Maturity ogives (proportion mature at age)

	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

Miscellaneous parameters

Steepness (Beverton & Holt stock-recruitment relationship)	0.80
Proportion spawning	1.0
Proportion of recruits that are male	0.5
Ageing error CV	0.08
Maximum exploitation rate (U_{max})	0.7

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 may exist in 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 are most similar to those from the west coast South Island, although, depending on which variables are used, they cannot always be distinguished from the Sub-Antarctic hake. However, the data are 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   Sub-Antarctic 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 from 2000 to 2010 and in 2012 and 2013. 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* surveys are shown in Figure 3 with further details given in Appendix A. There was some variation in the area surveyed within the November–December and April–May series. Consequently, multiple biomass estimates have been presented in Figure 3 for some of these surveys to show biomass estimates across consistent sets of strata. However, only the longest consistent time series (i.e., November–December 1991 area, April–May 300–800 m strata) are included as assessment model inputs.

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 biomass estimates from these surveys cannot be used as part of a consistent time series.
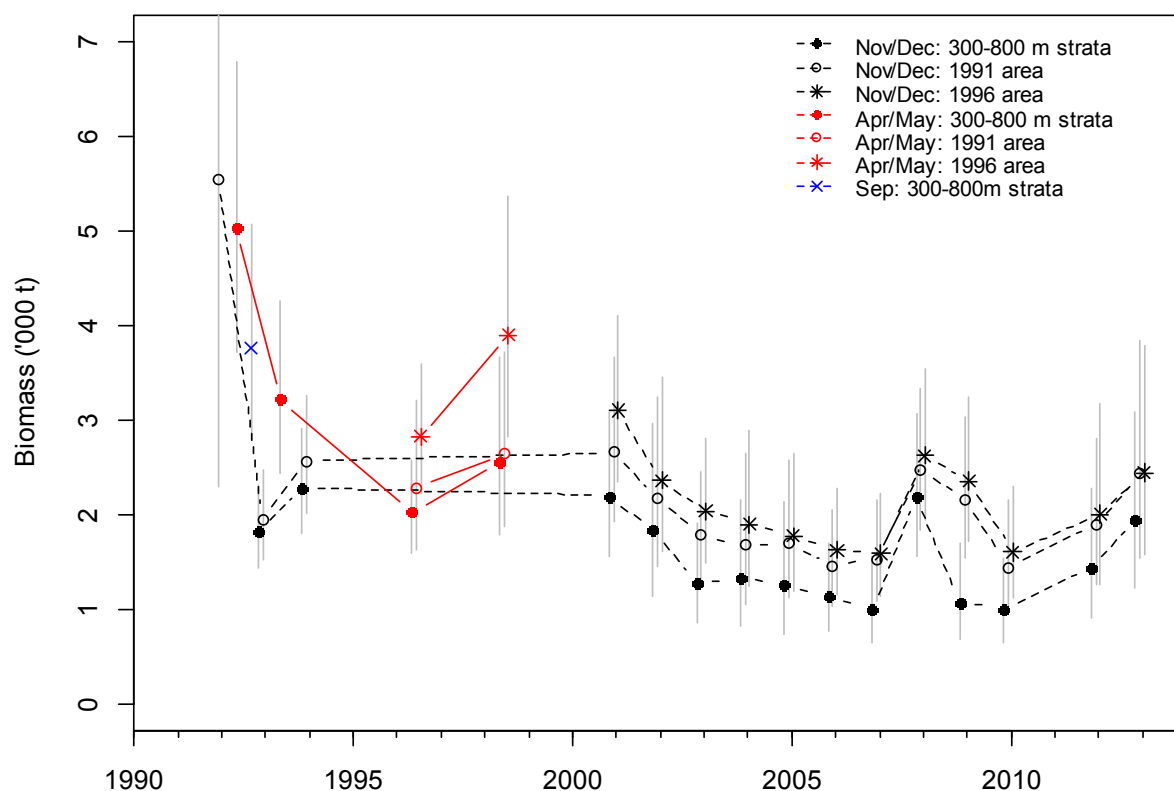
Figure 3: Hake biomass estimates from the *Tangaroa* surveys of the Sub-Antarctic (1991–2013, including the November–December, April–May, and September series), with approximate 95% confidence intervals as vertical grey bars. (See also Appendix A.)

3.4 Sub-Antarctic observer age data

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), was associated with the Snares-Pukaki area. Puysegur was the next most important area with about 3% of the catch. Available observer data were also concentrated in the Snares-Pukaki region, but it was clear that the smaller fisheries (particularly the Campbell Island area) were often over-sampled. Consequently, the Sub-Antarctic observer data were analysed as one major and three very minor fisheries, with a single fishery 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. However, it is 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 2012–13 (Horn & Sutton 2014).
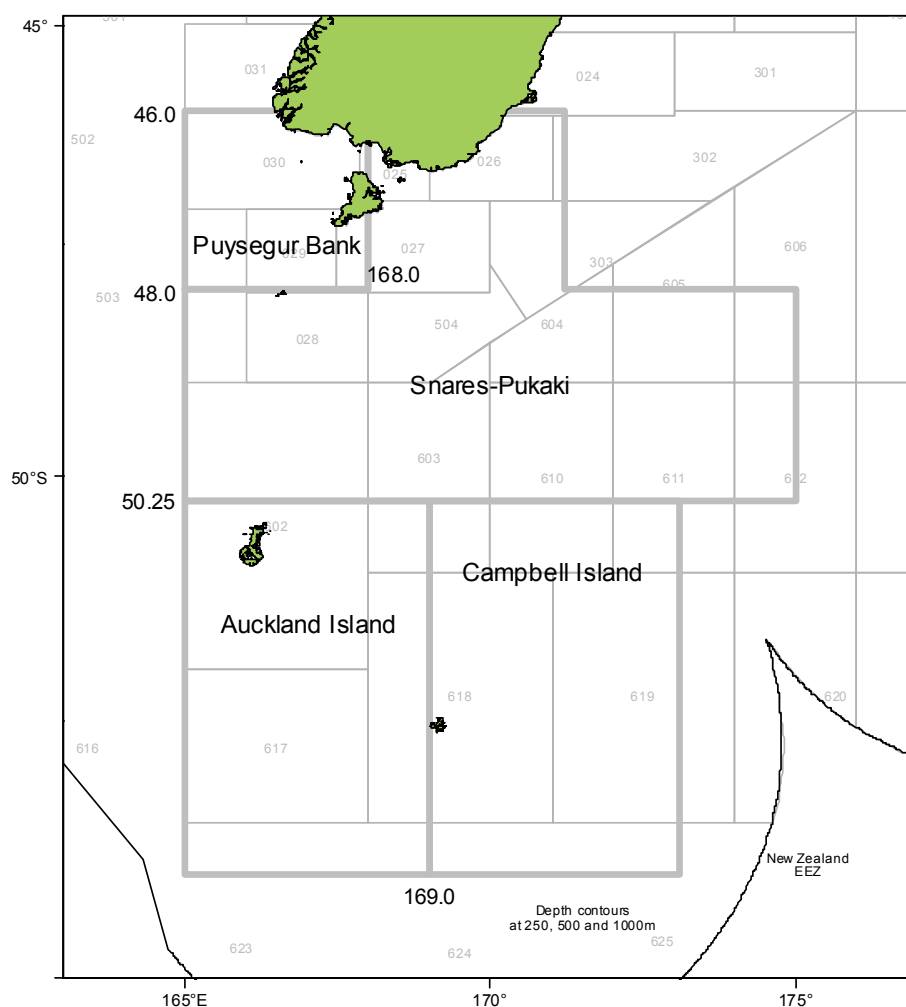
Figure 4: Fishery strata defined for the Sub-Antarctic hake fishery. Large numbers show latitudes or longitudes of fishery boundaries; small numbers denote statistical areas. Isobaths at 1000, 500, and 250 m are also shown.

3.5   CPUE indices

Standardised CPUE indices for the Sub-Antarctic stock were calculated by Ballara (2015) from TCEPR tow-by-tow data up the end of the 2012–13 fishing season (Table 6).

Table 6: Hake CPUE indices (and associated 95% confidence intervals and CVs) for the Sub-Antarctic trawl fishery (from Ballara 2015).

Year	Index	95% CI	CV	Year	Index	95% CI	CV
1991	1.19	1.19–1.37	0.07	2003	1.00	1.00–1.04	0.02
1992	1.18	1.18–1.25	0.03	2004	1.20	1.20–1.27	0.03
1993	1.37	1.37–1.45	0.03	2005	1.00	1.00–1.07	0.03
1994	1.04	1.04–1.12	0.04	2006	0.91	0.91–0.99	0.04
1995	0.84	0.84–0.89	0.03	2007	1.03	1.03–1.12	0.04
1996	0.93	0.93–0.99	0.03	2008	0.95	0.95–1.01	0.03
1997	1.04	1.04–1.10	0.03	2009	0.90	0.90–0.96	0.04
1998	1.11	1.11–1.16	0.02	2010	0.87	0.87–0.93	0.04
1999	1.03	1.03–1.08	0.02	2011	0.75	0.75–0.81	0.04
2000	1.13	1.13–1.18	0.02	2012	0.77	0.77–0.83	0.04
2001	1.14	1.14–1.18	0.02	2013	0.86	0.86–0.93	0.04
2002	1.00	1.00–1.04	0.02				

4. MODEL STRUCTURE, INPUTS, AND ESTIMATION

4.1 Introduction

An updated assessment of the Sub-Antarctic stock is presented here. The previous base case assessment of this stock (Horn 2013a) partitioned the population into age groups 1–30, with the last age class considered a plus group, and with sex excluded. Additional model runs were completed to investigate the effects of including sex in the partition, fitting to a trawl fishery CPUE series, and estimating instantaneous natural mortality in the model. The model's annual cycle began on 1 September and was divided into three steps. The current assessment model used the same annual cycle (Table 7), but maturity ogives were always fixed and maturity was never included in the partition. Note that model references to "year" within this document are labelled as the most recent calendar year, i.e., the year 1 September 1998 to 31 August 1999 is referred to as "1999". Some previous assessments of Sub-Antarctic hake have been based on fishing year, i.e., years starting on 1 October. However, landings peaks tend to occur from September to January (Ballara 2012), so it is logical to include the September catch with landings from the five months following it, rather than with catch taken about seven months previously.

Table 7: Annual cycle of the Sub-Antarctic stock model, showing the processes taking place at each time step, their sequence within each time step, and the available observations. Fishing and natural mortality that occur within a time step occur after all other processes, with half of the natural mortality for that time step occurring before and half after the fishing mortality.

					Observations	
Step	Period	Processes	M fraction[1]	Age fraction[2]	Description	$\%Z$[3]
1	Sep–Feb	Fishing, recruitment, and spawning	0.42	0.25	Summer survey	40
					Trawl CPUE	40
2	Mar–May	–	0.25	0.50	Autumn survey	50
3	Jun–Aug	Increment age	0.33	0.00	Spring survey	100

[1] The proportion of natural mortality that was assumed to have occurred in that time step.
[2] The age fraction (used for determining length at age) that was assumed to occur in that time step.
[3] $\%Z$ is the % of total mortality in the step that was assumed to have taken place at the time each observation was made.

For all subsequent models, estimates of fixed biological parameters used in the assessments are given in Table 5. A Beverton-Holt stock-recruitment relationship, with steepness 0.8, was assumed (Section 3.1). Variability in 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. The model's annual cycle was as described in Table 7.

Biomass estimates from the resource surveys were used as relative biomass indices, with associated CVs estimated from the survey analysis. The survey catchability constant (q) for each survey series was assumed to be constant across all years in that series. Three q values were estimated; one for each of the summer, autumn, and spring survey series. Although the summer and autumn series were believed to have different q values, no information was available to indicate whether the spring survey might have a q similar to either of the other series, so a separate q was estimated for it. Catch-at-age observations were available for each *Tangaroa* research survey, from a single *Amaltal Explorer* survey in November 1989, and from commercial observer data for the fishery. Two selectivity ogives were used for the survey catch-at-age data; one for the summer series (i.e., the *Tangaroa* and *Amaltal Explorer* data), and another for the autumn and spring *Tangaroa* data. There was no information to indicate that the *Amaltal Explorer* and the *Tangaroa* in summer had similar selectivities, or that the autumn and spring *Tangaroa* selectivities were the same. However, it was considered undesirable to estimate selectivity ogives for

single surveys (i.e., the *Amaltal Explorer* and the *Tangaroa* in spring), so they were analysed as described above. Lognormal errors, with known CVs, were assumed for all relative biomass observations.

The CVs (for observations fitted with lognormal likelihoods) are assumed to have allowed for sampling error only. Additional variance, assumed to arise from differences between model simplifications and real world variation, was added to the sampling variance for all observations in all model runs. Process error of 0.2 was added to all survey biomass indices following the recommendation of Francis et al. (2001). For CPUE indices, process error CVs were estimated following Francis (2011).

For the proportions-at-age observations from the trawl survey and fishery, a multinomial error distribution was assumed. Process errors for the catch-at-age series were captured by the effective sample sizes per year, used in the multinomial likelihood, which were estimated iteratively using method TA1.8 described in Francis (2011). 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.

Year class strengths were assumed known (and equal to one) for years before 1974 and after 2013, 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 multipliers is used here (see Bull et al. (2012) for details).

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 2012–13 were allocated to month and fishery based on reported date and location (Ballara 2015). Annual totals were obtained by summing the monthly totals using a September to August year (for reasons described above). Thus, catch histories for model years 1990 to 2013 were produced for the Sub-Antarctic section of HAK 1 (Table 8). Annual catches before 1990 are as presented in Table 4.

Table 8: Estimated catch (t) from the Sub-Antarctic stock, by fishing year, and model year. 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. Model year landings from 2014 are estimated assuming catch patterns similar to the previous year.

Fishing year	Catch (t)	Model year	Catch (t)	Fishing year	Catch (t)	Model year	Catch (t)
1974–75	120	1975	120	1994–95	1 771	1995	1 995
1975–76	281	1976	281	1995–96	2 884	1996	2 779
1976–77	372	1977	372	1996–97	2 262	1997	1 915
1977–78	762	1978	762	1997–98	2 606	1998	2 958
1978–79	364	1979	364	1998–99	2 796	1999	2 854
1979–80	350	1980	350	1999–00	3 020	2000	3 108
1980–81	272	1981	272	2000–01	2 790	2001	2 820
1981–82	179	1982	179	2001–02	2 510	2002	2 444
1982–83	448	1983	448	2002–03	2 738	2003	2 777
1983–84	722	1984	722	2003–04	3 245	2004	3 223
1984–85	525	1985	525	2004–05	2 539	2005	2 592
1985–86	818	1986	818	2005–06	2 557	2006	2 541
1986–87	713	1987	713	2006–07	1 818	2007	1 711
1987–88	1 095	1988	1 095	2007–08	2 202	2008	2 329
1988–89	1 237	1989	1 237	2008–09	2 427	2009	2 446
1989–90	1 917	1990	1 897	2009–10	1 958	2010	1 927
1990–91	2 370	1991	2 381	2010–11	1 288	2011	1 319
1991–92	2 743	1992	2 810	2011–12	1 892	2012	1 900
1992–93	3 254	1993	3 941	2012–13	1 863	2013	1 859
1993–94	1 450	1994	1 596	2013–14	1 771	2014	1 800

4.2   Prior distributions and penalty functions

The assumed prior distributions used in the assessment are given in Table 9. The priors for B_0 and year class strengths were intended to be relatively uninformed, and had wide bounds. The prior for the 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 Sub-Antarctic hake assessment (Horn 2013a). A 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 (Figure 5). Priors for all selectivity parameters were assumed to be uniform. 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.

Penalty functions were used a) 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, b) to ensure that all estimated year class strengths averaged 1, and c) to smooth the year class strengths estimated over the period 1974 to 1979. The justification for the smoothing of year class strengths in the 1970s was provided by Horn (2013a).

Table 9: The priors assumed for estimated parameters. The given parameters for the priors are mean (in natural space) and CV

Parameter description	Distribution	Parameters		Bounds	
B_0	Uniform-log	–	–	5 000	350 000
Year class strengths	Lognormal	1.0	1.1	0.01	100
Trawl survey q[1]	Lognormal	0.16	0.79	0.01	0.4
CPUE q	Uniform-log	–	–	1e-8	1e-3
Selectivities	Uniform	–	–	0	20–200[2]
M (x_0, y_0, y_1, y_2)[3]	Uniform	–	–	3, 0.01, 0.01, 0.01	15, 0.6, 1.0, 1.0

[1] Three trawl survey q values were estimated, but all had the same priors.
[2] A range of maximum values was used for the upper bound.
[3] x_0, age at minimum M; y_0, M at x_0; y_1, M at the minimum age in the partition; y_2, M at the maximum age in the partition.
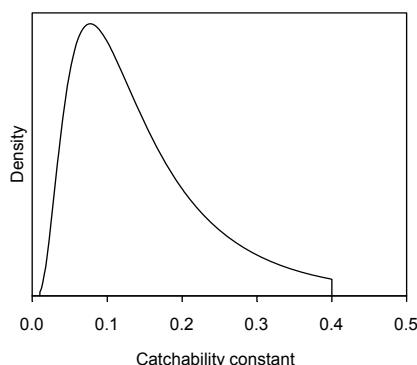
Figure 5: The prior distribution for all three of the survey catchability constants (q), lognormal where μ=0.16, CV=0.79, and bounds (0.01,0.40).

4.3 Developing a 'base' model

Some initial investigations were completed to develop a 'base' model. Model parameters were estimated for final model runs using Bayesian estimation implemented using the CASAL software. However, only the mode of the joint posterior distribution (MPD) was estimated in these initial runs. All runs included survey biomass indices and proportion-at-age data, and the fishery catch-at-age data. Trawl fishery CPUE was included only in a sensitivity run; it was not considered to be a reliable index of biomass owing to changes over time in fishing behaviour and catch reporting practices (Ballara 2015). Full details of the CASAL algorithms, software, and methods were detailed by Bull et al. (2012).

Following the previous assessment of HAK 1 (Horn 2013a) it was concluded that future assessments should adopt the recommendations of Francis (2011) relating to data weighting, i.e.,
- use multinomial, rather than lognormal, errors for at-age data;
- use method TA1.8 from Francis (2011) for stage-2 weighting of at-age data;
- use a lowess smoother (or similar) to set a (total) CV for CPUE data.

It was apparent that the sex ratio information for the trawl surveys and commercial fishery were inconsistent (Horn 2013a). Sex ratios in the surveys were relatively consistent over time, with perhaps a weak trend of increasing proportions of males over time (Figure 6). However, the samples from the commercial catch were indicative of an increasing proportion of males being removed from the population over time (Figure 6). If proportionally more males were removed in recent years then the surveys would be expected to show a reduction in the proportion of males over time. It was also found that male proportion-at-age data from the fishery were consistently poorly fitted relative to female data; the residuals for male data points were, on average, 1.5 times greater than for female data (Horn 2013a). Similar characteristics were observed in the Chatham Rise and west coast South Island hake fisheries, and the Chatham Rise fishery also exhibited similar conflicts in sex ratio trends. However, for both those stocks, the subsequent modelling problems were alleviated by removing sex from the partition (Horn & Francis 2010, Horn 2011). This is not an ideal solution, however, because there are marked differences in growth between sexes. Consequently, some investigations below looked at returning sex to the partition.
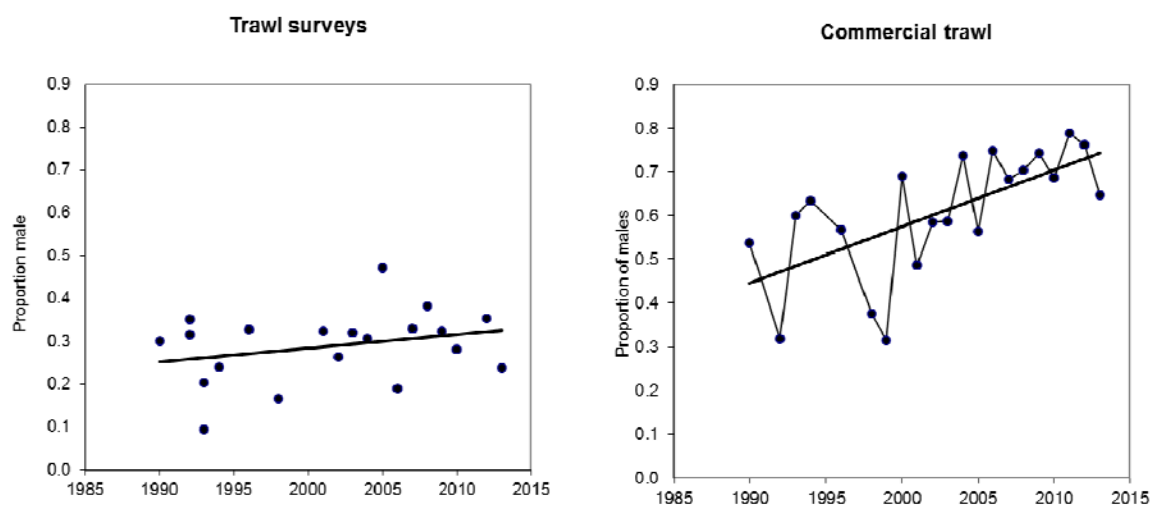
Figure 6: Proportion of male fish recorded in trawl surveys (scaled to survey area) and in the observer length data for the commercial trawl fishery (scaled to total catch by year). Solid lines are linear regressions.

In developing a base model a series of eight models was considered, with each new model typically differing from a previous model in only one key assumption (Table 10). The starting model was similar to the base model from the previous assessment (i.e., single sex, smoothed 1974–79 year-class strengths, all selectivities domed), but with new data included (i.e., catches, survey biomass estimates, survey and

fishery at-age data), and with the recommendations of Francis (2011) adopted (i.e., multinomial error structure and stage-2 weighting for at-age data). The need for the smoothing of the 1974–79 year-class strengths was re-investigated, given the change from lognormal to multinomial errors, and was found to be still necessary to avoid widely fluctuating estimates that were not supported by the data (see Horn 2013a).

All models estimated an absolute biomass trajectory, year class strengths from 1974 to 2010, fits to any included relative abundance series, selectivity ogives for the trawl surveys and trawl fishery, and trawl survey catchability coefficients. Two models also estimated instantaneous natural mortality.

Table 10: Brief description of the assumptions that differed amongst the eight models that were considered in developing a base case model (see text for more detail). For each model, the underlined assumption is the main one that distinguished it from preceding models.

							Model number	
Assumption	1	2	3	4	5	6	7	8
Selectivities domed, single sex	Y	Y	Y	Y	N	Y	Y[1]	Y[1]
Selectivities domed and by sex	N	N	N	N	$\underline{Y}$	N	N	N
Biological parameters sex-based	N	Y	Y	Y	Y	Y	Y	Y
Observations sex-based	N	N	$\underline{Y}$	Y	Y	Y	Y	$\underline{N}$
Sex in partition	N	$\underline{Y}$	Y	Y	Y	Y	Y	Y
p_male estimated in model	N	N	N	$\underline{Y}$	N	N	N	N
CPUE data used	N	N	N	N	N	$\underline{Y}$	N	N
M estimated in model as an ogive	N	N	N	N	N	N	$\underline{Y}$	Y

[1] Logistic selectivities were used for the trawl fishery in models 7 and 8.

An initial model (model 1) was set up, partitioning the population into age groups 1–30, with the last age class a plus group. The partition did not include sex or maturity. The model used three selectivity ogives: survey selectivities for the summer resource survey series, survey selectivities for the autumn and spring resource survey series, and selectivities for the commercial trawl fishery. Selectivities were assumed constant across all years in the fishery and the research surveys. All selectivity ogives were estimated using the double-normal parameterisation. No CPUE data were incorporated.

For the initial model B_0 was 107 220 t, and stock status in 2014 was estimated to be 53% of B_0. The two survey biomass series with multiple points appeared to be reasonably well fitted, with no obvious trends in the residuals (Figure 7). As in previous assessments the spawning biomass was estimated to have increased markedly in the 1980s, before the survey series started, and this increase was driven primarily by the extremely strong year class in 1980 (Horn 2013a).

A second model (model 2) included sex in the partition, with biological parameters provided by sex, but with the observations unsexed. The biomass trajectory was little different to that from model 1 (B_0 was 109 080 t, and B_{2014} was 54% of B_0), as were the fits to the trawl survey series (Figure 7). The total negative log likelihood from the two models were the same. Fits to the survey and fishery at-age observations looked reasonable in most years (Figures B1 and B2).
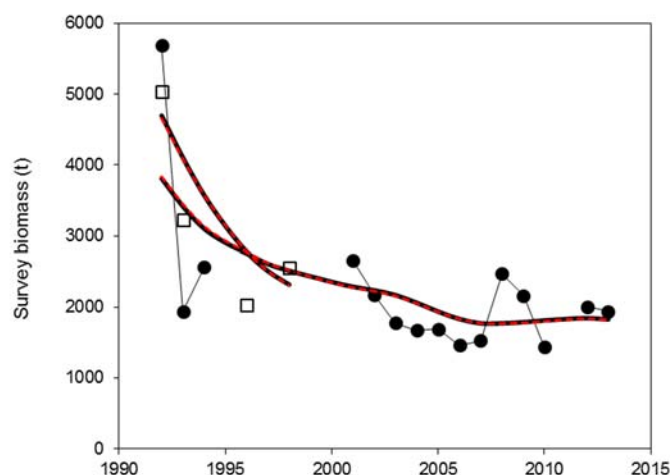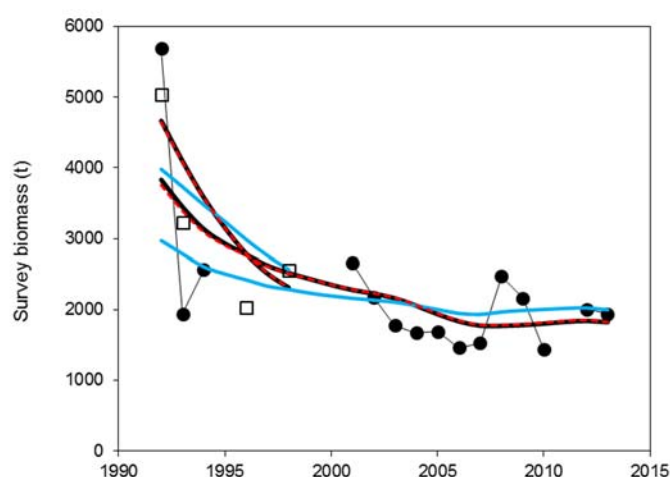
Figure 7: Fits to the summer (observed values as solid circles) and autumn (open squares) research survey series, for model 1 (dashed black lines) and model 2 (dashed red lines). The fits overlap almost exactly.

Model 3 was identical to model 2 except that the observations were sexed (i.e., numbers-at-age, by sex). This change also had little impact on estimates of biomass or stock status (B_0 was 106 550 t, and B_{2014} was 54% of B_0), or on fits to the trawl survey series (Figure 8, Table 11). The trawl survey at-age observations are generally below the fitted line for males (Figure B6) and above the fitted line for females (Figure B5), while the reverse is generally apparent for the trawl fishery at-age observations (Figures B3 and B4). There was some indication of trends over time for the trawl fishery data (as might be expected given the apparent change in proportion male (see Figure 6). For males, the observed points are around, or even below, the fitted line for the first six years, but generally above the fitted line in the latter half of the series (Figure B4). For females, the observations are around, or even above, the fitted line for the first seven years, but quite consistently below the fitted line from 2002 onwards (Figure B3).

Model 4 was identical to model 3 except that the proportion of recruits that were males was estimated (instead of the assumption that it was 0.5). The estimated value for p_male was 0.506, resulting in very minor changes to the model outputs and the fits to the at-age observations (Table 11).

Figure 8: Fits to the summer (observed values as solid circles) and autumn (open squares) research survey series, for model 2 (black lines), model 3 (dashed red lines), and model 5 (blue lines).

Model 5 was the same as model 3 except that the selectivity ogives were estimated by sex. This change had a moderate impact on estimates of biomass and stock status (B_0 was 116 540 t, and B_{2014} was 70% of B_0),

and on the fits to the trawl survey series (Figure 8). Estimated absolute biomass was higher, and current stock status was more optimistic than for model 3 (Figure 9). The fits to the survey series were both flatter than in all previous models, although gains in log likelihood were relatively slight (Table 11). There were some changes in estimated year class strengths, with estimates from model 5 being generally lower in the 1970s and higher in the 2000s than for model 3 (Figure 9). The overall log likelihood (relative to model 3) improved by 93 points, with most of the gain coming from improved fits to the at-age data from the summer survey series and the trawl fishery (Table 11). An examination of the fits to the observed at-age data from the trawl surveys shows no consistent bias by sex (as was apparent for the model 3 data), and the fits ranged from reasonable to poor (Figures B9 and B10). Fits to the male trawl fishery at-age data ranged from good to poor, with the observed points in the first third of the series often below the fitted line (Figure B8). For female fishery data, the fits were also good to poor, with the observed data from the latter half of the series often being below the fitted line (Figure B7). The trends over time in the fits to the trawl fishery data in model 5 were not as marked as in model 3. Overall, the fits when sexes were combined (Figures B1 and B2) appeared, by eye, to be slightly better than when at-age observations were sexed (Figures B3–B10).

Table 11: Negative log likelihood of all data series for models 2–5. The log likelihood values for the age data in model 2 are not comparable with those from the other models because the data are unsexed in model 2 and sexed in all other models. The gains in log likelihood from model 3 to model 5 show how the inclusion of selectivity by sex improves the fits, particularly for the summer trawl survey.

Data series	Model 2	Model 3	Model 4	Model 5	Gain (3 to 5)
Survey biomass (summer)	-12.9	-13.1	-13.1	-13.7	0.6
Survey biomass (autumn)	-4.4	-4.4	-4.4	-3.7	-0.7
Survey biomass (spring)	-1.3	-1.3	-1.3	-1.4	0.1
Survey age (summer)	369.3	567.9	570.7	527.7	40.2
Survey age (autumn)	59.7	87.5	87.8	84.9	2.6
Survey age (spring)	15.1	22.3	22.4	23.1	-0.8
Fishery age	405.1	690.9	687.6	640.4	50.5
Priors and penalties	2.1	2.0	2.0	0.7	1.3
Total log likelihood	832.7	1351.7	1351.6	1258.0	93.7
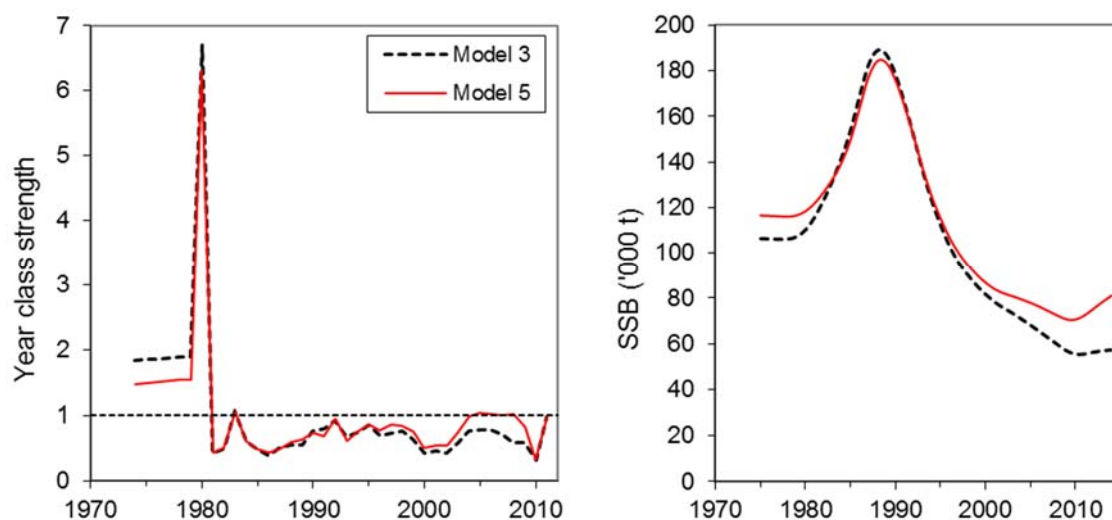
Figure 9: Estimated year class strengths and spawning stock biomass (SSB) from models 3 and 5.

Including at-age observations with or without sex made little difference to the resulting selectivity ogives if selectivity was estimated for sexes combined (Figure 10). However, when selectivity was estimated by sex (see bottom panel of Figure 10) the shapes of the ogives varied markedly between males and females, particularly for the summer survey, and this was believed to be unsatisfactory and unrealistic. The effect of forcing logistic selectivity ogives for the research surveys was examined previously (Horn

2013a) with the underlying assumption being that the surveys sample all the adult population, but the overall fits were much worse than with double-normal ogives. Consequently, it was concluded that if a constant value is used for natural mortality, at-age data from all sources are much better fitted by ogives that are double-normal, rather than logistic.
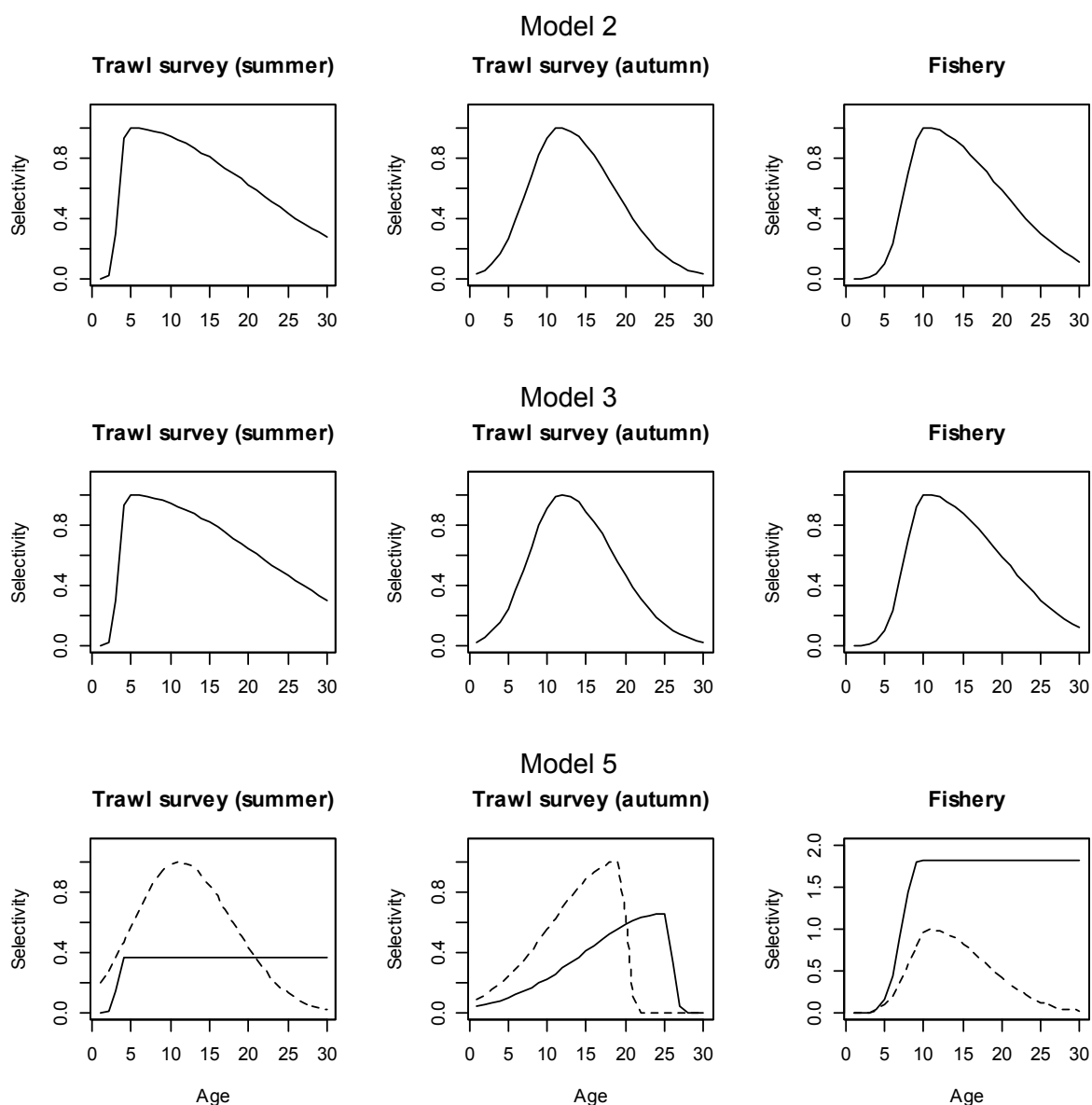

Figure 10: MPD estimates of trawl survey and fishery selectivity from models 2 and 3 (selectivity unsexed), and for model 5 for males (solid line) and females (dashed line).

A likelihood profile for model 3 showed that all the groups of inputs either provided little information on B_0 or strongly rejected values of B_0 less than 60 000 t (Figure 11). Only the priors and penalties precluded a very large estimate of virgin biomass. However, biomass levels greater than about 160 000 t would require exceptionally low trawl survey q values (i.e., less than 0.02), and would be inconsistent with B_0 estimates for other New Zealand hake stocks, i.e., 37 000 t and 89 000 t for the Chatham Rise and west coast South Island stocks, respectively (Horn 2013b). Likelihood profiles for model 5 showed that the summer survey and its age data, and the fishery age data supported B_0 values greater than 90 000 t, the autumn survey supported a value lower than 160 000 t, and the priors and penalties supported a very low B_0. Overall, there was strong support for B_0 to be in the range 80 000–150 000 t (Figure 11). There appear to be several local likelihood minima in this range.
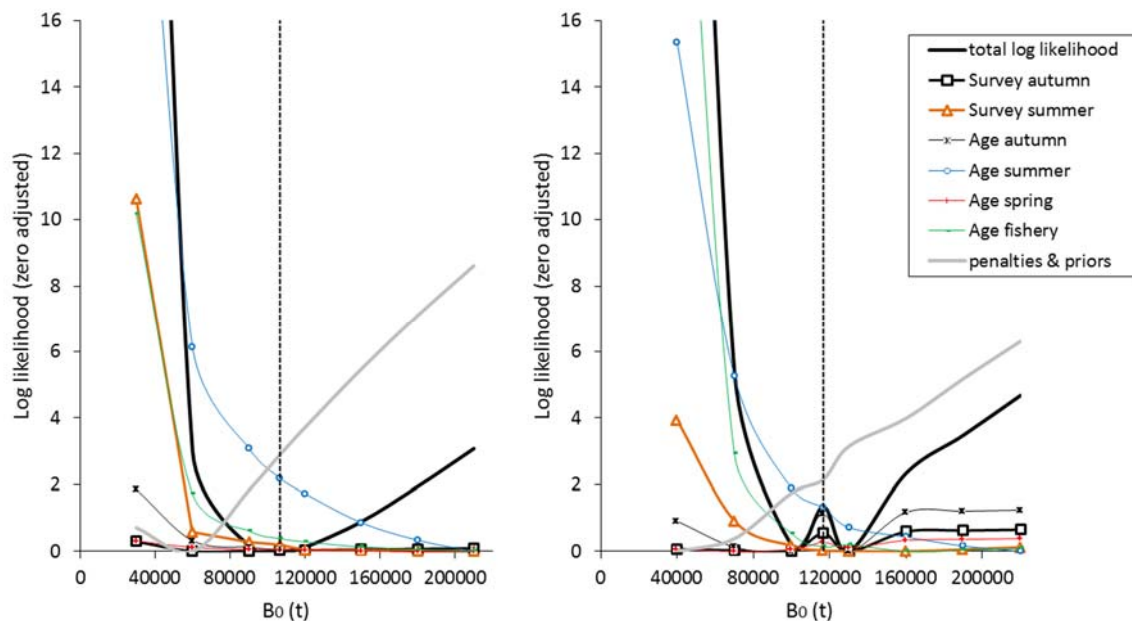
Figure 11: Likelihood profile on B_0 for model 3 (left panel) and model 5 (right panel), showing both the total likelihood (heavy line) and those for individual data series. Vertical dashed line shows the model estimate of B_0.

Model 6 examined the impact of adding a trawl fishery CPUE series to model 3, and found that it made little change to the estimate of B_0, but produced a relatively lower biomass peak in the late 1980s (Figure 12). The flatter biomass trajectory resulted in a more optimistic stock status in 2014 of 73% of B_0 (compared to 54% B_0 for model 3). The estimated year class strengths were lower in the 1970s, but generally higher since 1987 (Figure 12). The CPUE series is relatively well fitted (Figure 13). Inclusion of the CPUE encourages flatter (but not clearly worse) fits to the trawl survey series, with only the 1992 summer survey point appearing to be poorly fitted (Figure 13). The total negative log likelihood for the three research survey series improved by 0.7 points in model 6, relative to model 3.
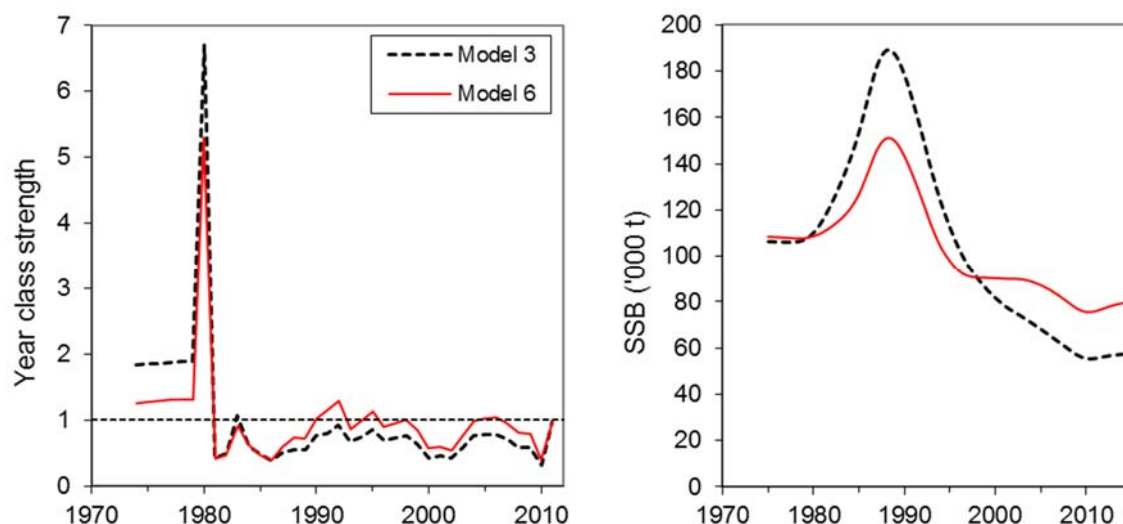
Figure 12: Estimated year class strengths and spawning stock biomass (SSB) from models 3 and 6.
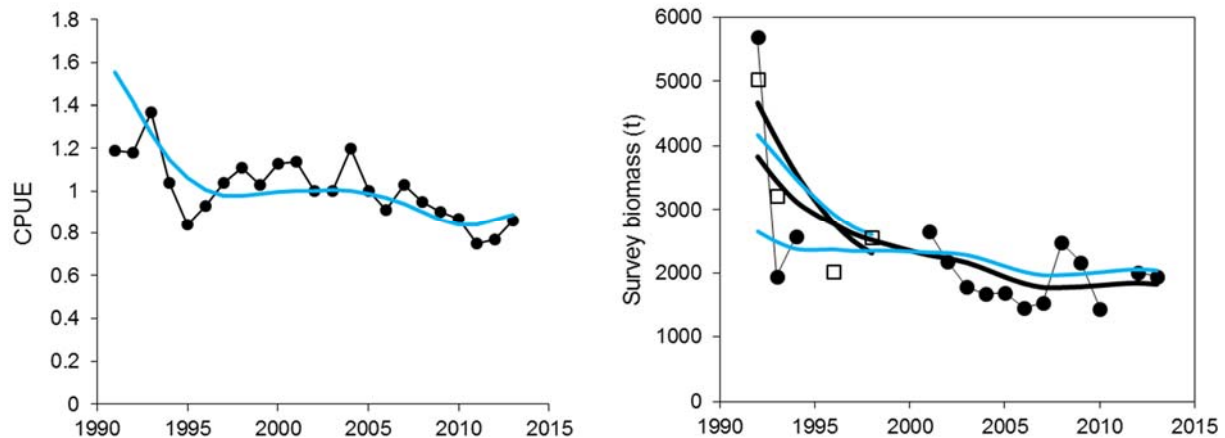
Figure 13: Left panel – Fits to the CPUE series in model 6. Right panel – Fits to the summer (observed values as solid circles) and autumn (open squares) research survey series, for model 3 (thick black lines) and model 6 (blue lines).

The data for this stock comprise a large amount of catch-at-age information so it was considered desirable to investigate the estimation of M in the model. Because M is confounded with selectivity, the model run where M was estimated (model 7) was similar to model 3 but it had the selectivity ogive for the trawl fishery estimated using the logistic (rather than double-normal) parameterisation, with the underlying assumption being that because the fishery is concentrated on spawning aggregations (Ballara 2015) it comprehensively samples all the adult population. In model 7, M was estimated using the double exponential parameterisation. By allowing the model to estimate an age-dependent M, the fits to the age data from the trawl fishery were improved, while those for the three survey series were slightly degraded (Table 12). The overall model fit was improved slightly.

Table 12: Negative log likelihood of all data series from models 3 and 7, showing how estimating M as age-dependent and forcing the fishery ogive to be logistic improved the fit to the fishery at-age data.

Data series	Model 3	Model 7	Gain
Survey biomass (summer)	-13.1	-13.3	0.2
Survey biomass (autumn)	-4.4	-4.3	-0.1
Survey biomass (spring)	-1.3	-1.4	0.1
Survey age (summer)	567.9	577.3	-9.4
Survey age (autumn)	87.5	90.3	-2.8
Survey age (spring)	22.3	22.9	-0.6
Fishery age	690.9	667.3	23.6
Priors and penalties	2.0	-0.7	2.7
Total log likelihood	1351.7	1338.1	13.6

The estimated ogive for M was logical with a minimum at age 8 (slightly lower than the estimated age at 100% maturity of 10 years), and a range from 0.09 to 0.96 (Figure 14). The impact of estimating M was a marked decrease in the estimate of B_0 (60 210 t, down from 106 550 t in model 3) (Figure 15). It had comparatively little effect on the estimated year class strengths (the earliest estimates were lower, and those since 1995 were higher), and also resulted in only slight changes in the fits to the trawl survey series (slightly flatter trajectories) (Figure 15). The biomass trajectory still exhibits a steep decline throughout the 1990s, resulting in a stock status in 2014 of 59% of B_0 (compared to 54% B_0 for the base model). Selectivity ogives are shown in Figure 16.
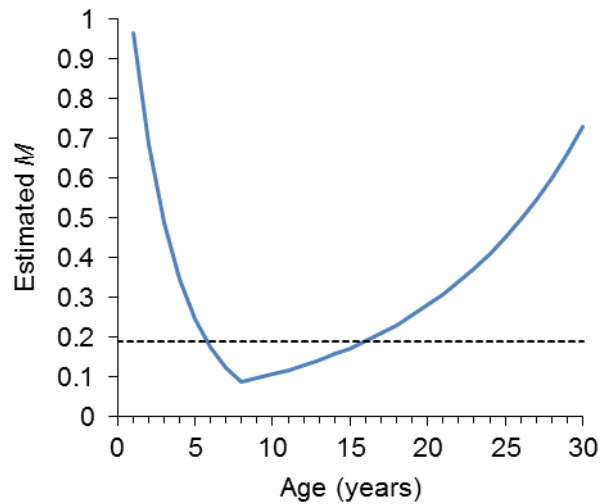
Figure 14: Estimated *M* ogive from model 7. The horizontal dashed line indicates the constant *M* of 0.19 used in all other model runs.
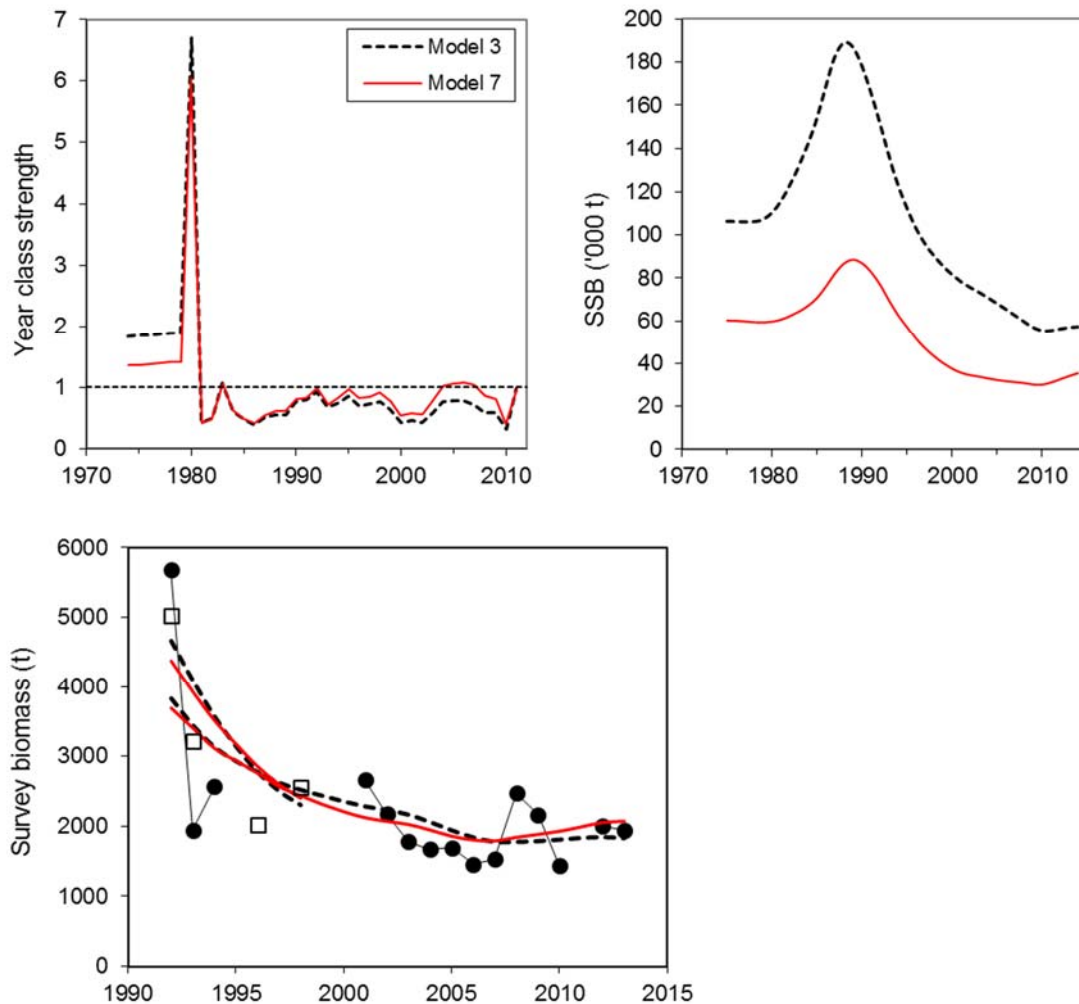

Figure 15: Estimates of year class strengths, biomass trajectories, and fits to the trawl survey series from model 3 (sexes combined selectivity model) and model 7 (estimate *M* model, with sexed observations).
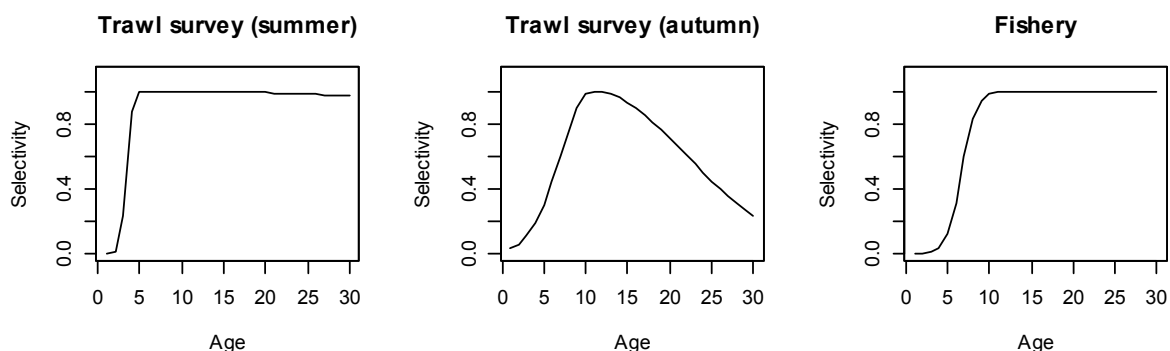
Figure 16: MPD estimates of trawl survey and fishery selectivity from model 7 (estimate *M* model, with sexed observations).

A final model (model 8) estimated *M*, again with the fishery ogive assumed to be logistic, but this time with the inputs and structure of model 2 (i.e., unsexed observations, but biological parameters by sex). The results were little different to those from model 7 depicted in Figures 14 and 15. B_0 was 61 570 t and B_{2014} was 59% of B_0. Selectivity ogives were also little different (Figure 17).
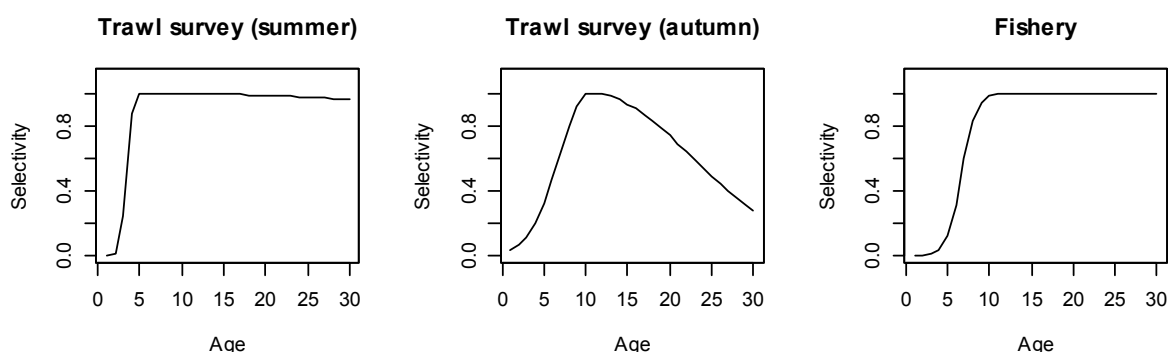
Figure 17: MPD estimates of trawl survey and fishery selectivity from model 8 (estimate *M* model, with unsexed observations).

Results from the eight model runs generally showed that:
- Sex in or out of partition had little impact on biomass or stock status
- Sexed or unsexed selectivity had little impact on biomass or stock status
- Estimation of *M* had a significant impact on biomass (but less impact on stock status)
- Estimation of *M* resulted in lower estimates of absolute biomass, and a more realistic estimate of trawl survey catchability (than constant *M* models)
- When selectivity was estimated by sex, the ogives varied markedly between sexes and so were unrealistic
- All models with sexed observations exhibited trends in the fits to these data (over time, and by sex)

Consequently, the model that best avoided undesirable fitting trends and produced the most believable selectivity ogives and trawl survey *q*s was model 8 (with unsexed observations, unsexed selectivity, and estimation of age-dependent *M* in the model).

Following the presentation of the above MPD model fits to the Deepwater Fisheries Working Group it was concluded that the best base case model for MCMC estimation was model 8, but with the trawl fishery ogive allowed to be double-normal (rather than being forced to be logistic). MPD fits and ogives derived from this model are shown in Figure 18, and likelihood profiles for B_0 and the minimum value for *M* are presented in Figure 19. Relative to model 8, the fishery ogive has not changed much, particularly given that few fish in the survey or fishery samples are older than 20 years. Changing the allowable fishery ogive structure also produced negligible changes in the estimates of *M* at age.
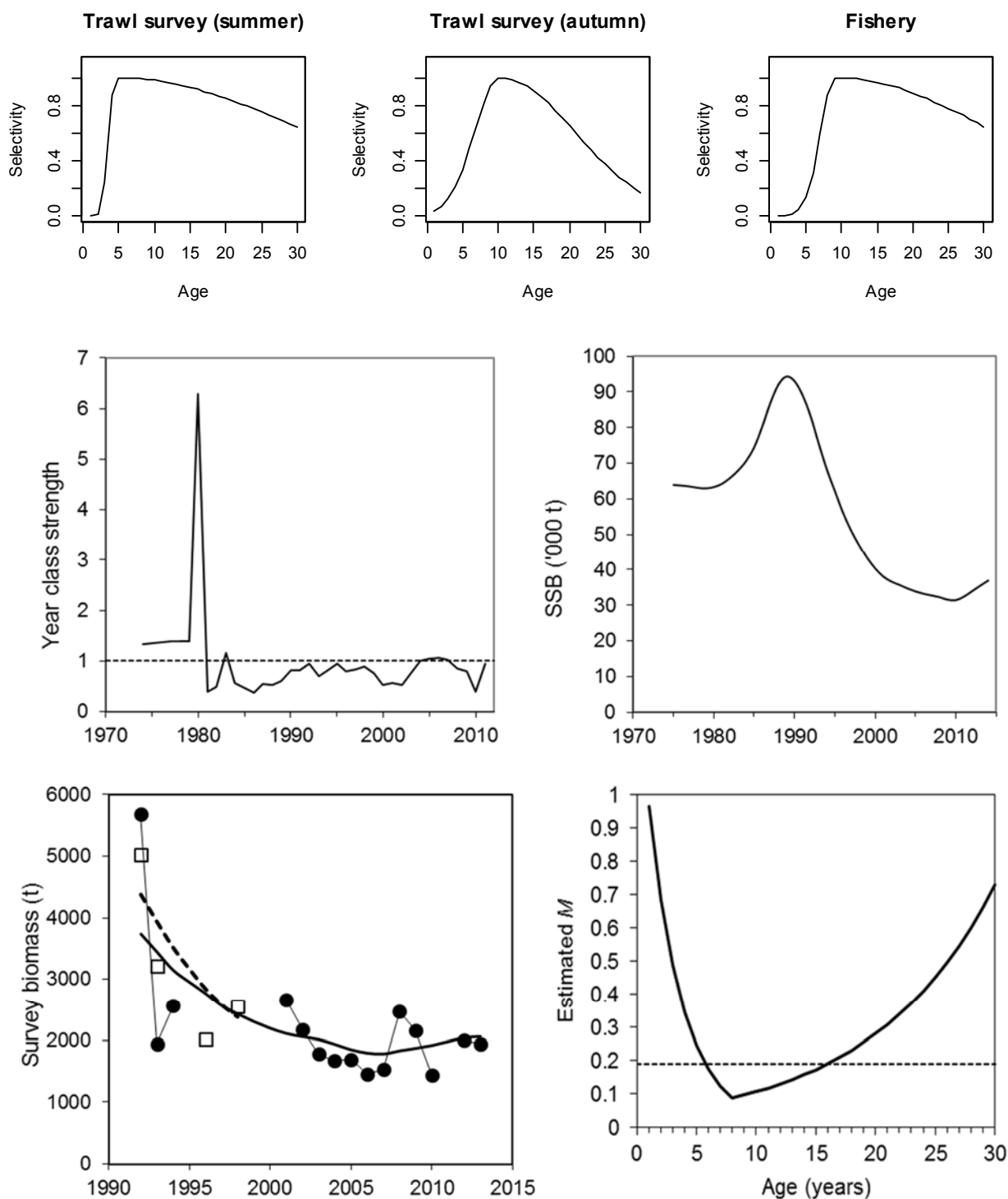
Figure 18: Estimates of selectivity ogives, year class strengths, biomass trajectory, fits to the trawl survey series, and *M* at age, from the base model.

The likelihood profile for B_0 showed that all the groups of inputs either provided little information on B_0 or strongly rejected values of B_0 less than about 50 000 t, and the summer survey age data encouraged a value less than 160 000 t (Figure 19). The priors and penalties encouraged a virgin biomass in a relatively narrow range from 40 000 to 80 000 t; the minimum value is driven primarily by the prior on recruitment, while the priors on the trawl survey *q*s discourage low and high biomass values (Figure 19). The age data from the fishery and summer survey series were the main influences on *M*, encouraging a minimum *M* value between 0.05 and 0.13 (Figure 19). Overall it was apparent that the model estimates of B_0 and *M* were

determined primarily by the input data and not by the priors, with only the informative priors on trawl survey qs having any influence.
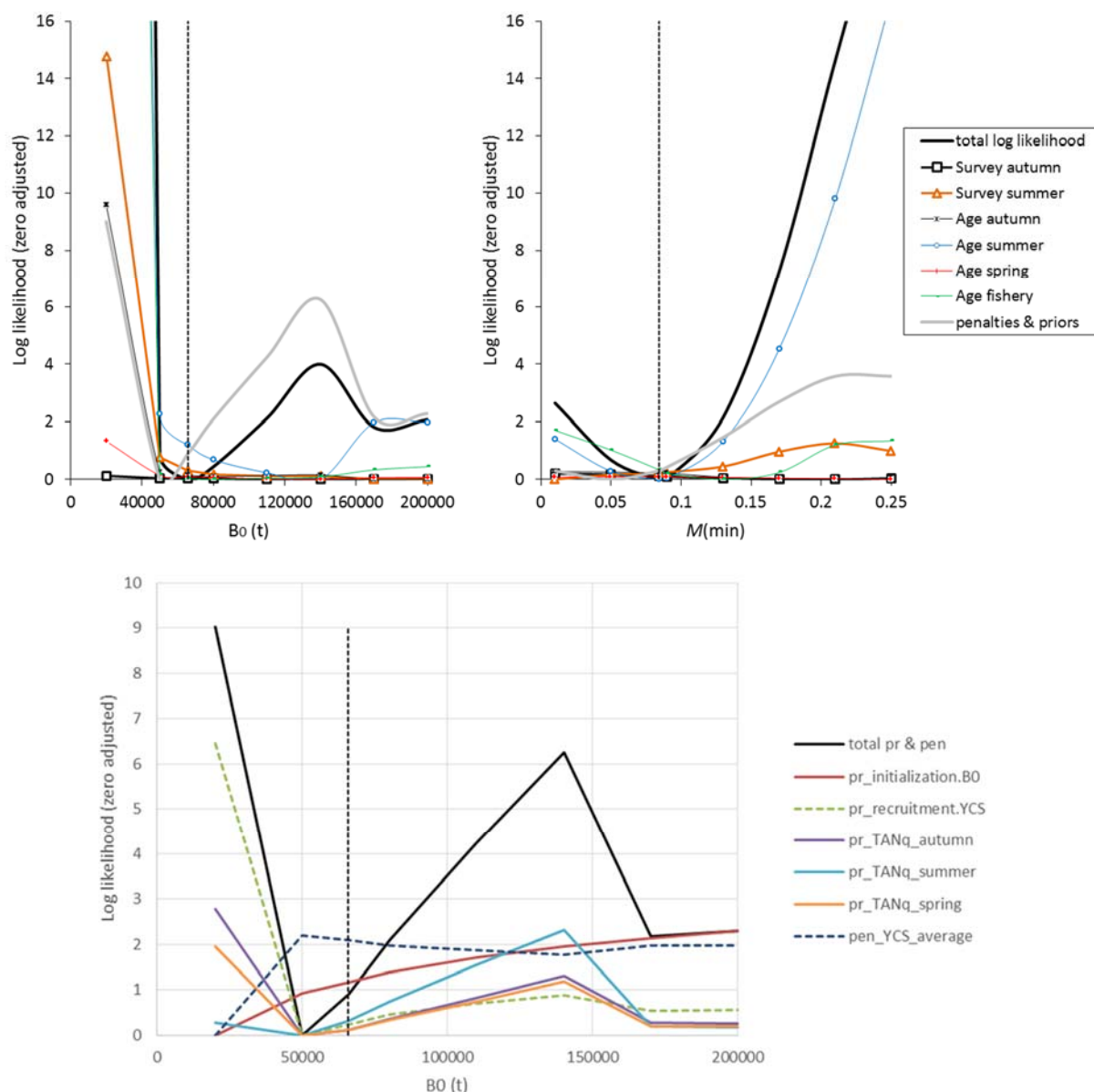
Figure 19: Likelihood profile on B_0 (top left panel) and the minimum value of M (top right panel) for the base model, showing both the total likelihood (heavy line) and those for individual data series. Likelihood profile on B_0 for the priors (pr) and penalties (pen) only is shown in the bottom panel. Vertical dashed lines show the model estimates of B_0 and M.

4.4   Model estimation using MCMC

As well as a base model run, sensitivity model runs using MCMC estimation were also completed to investigate:

- halving the effective sample sizes of the composition data (the half N_{eff} model),
- the estimation of M as a sex-dependent constant (the estimate M model),
- fixing M at the previously used default values of 0.20 for males and 0.18 for females (the fixed M model),
- the inclusion of the trawl fishery CPUE series (the CPUE model).

Model parameters were derived using Bayesian estimation implemented using the CASAL v2.30 software. The q values for the trawl surveys (and the CPUE when it was fitted) were estimated as free parameters, unlike in previous assessments when they were estimated as nuisance parameters. This change can result in difficulties with the model achieving convergence, so a much longer initial chain length and burn-in period (relative to the previous assessment) were used to ensure that convergence had occurred. 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 2×10^7 iterations, a burn-in length of 1.75×10^7 iterations, and with every 2500th sample kept from the final 2.5×10^6 iterations (i.e., a final sample of length 1000 was taken from the Bayesian posterior). Year class strengths were estimated as in the MPD runs except that values for 1974–79 were not smoothed and those for 2011–13 were no longer fixed at 1.

5. MODEL ESTIMATES

Estimates of biomass were made using the biological parameters (see Table 5) and model input parameters described earlier. MCMC estimates of the posterior distribution were obtained for all five model runs (i.e., base, half N_{eff}, estimate M, fixed M, and CPUE), 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_{2014} from the base model appear reasonably well converged (Figure 20). The distributions of estimates of B_0 and B_{2014} (as %B_0) from the base model are reasonably consistent between the first, middle, and last thirds of the chain (Figure 20), so convergence is probably adequate for stock-assessment purposes.

The estimated MCMC marginal posterior distributions for selected parameters from the single sex model are shown in Figures 21–26. The selectivity ogives for the trawl survey series and the trawl fishery were all essentially logistic shaped, despite their double-normal parameterisation (Figure 21). The ogives suggest that hake were fully selected by the fishery by age 10, and that younger fish were more selected by the summer trawl survey (as would be expected given the smaller codend mesh). However, age at full selectivity for the autumn survey is the highest at 15 years, although the confidence bounds around this ogive are much wider than for the other two. There is no information outside the model that allows the shape of the estimated selectivity ogives to be verified.

Year class strength estimates were well estimated for all years from 1982 to 2010, and moderately well estimated in all other years (Figure 22). The 1980 year class stands out as being exceptionally strong, but variation in year class strength since then does not appear to be great with virtually all median estimates being between 0.5 and 2.

The instantaneous natural mortality (M) ogive estimated independent of sex had a minimum of about 0.11 at 9 years, rising to about 0.7 at 30 years, and a relatively narrow 95% credible interval across ages 6 to 23, i.e., the age classes most abundant in the surveys and the commercial catch (Figure 23). However, the estimation of M will be confounded with the estimation of survey and fishery selectivities, so we cannot be confident that the true ogive has been determined here.

Estimated biomass for the Sub-Antarctic stock increased throughout the 1980s owing to relatively low catch levels, and the recruitment of stronger than average 1977 to 1980 year class (Figure 24). Biomass then steadily declined from 1990 to about 2000 owing to higher levels of exploitation (Figure 25) and the recruitment of year classes that were generally of below-average strength. A slower decline continued to about 2010, with a slight increase since then being a consequence of the recruitment of six consecutive year classes since 2004 that are estimated to be about average strength, and a decline in exploitation levels. Bounds around the biomass estimates are wide, with current stock size being about 60% of B_0 (95% credible interval 44–78%) (see Figure 24 and Table 13). Exploitation rates (catch over vulnerable biomass) were negligible (less than 0.02) up to 1990, and have probably not exceeded 0.1 yr^{-1} in any year since then (Figure 25).

The research survey catchability constants are estimated to be about 4%, 7% and 7% for the summer, autumn and spring survey series, respectively, suggesting that the absolute catchability of all the surveys is low, and, particularly for the summer series, somewhat inconsistent with the prior (Figure 26).
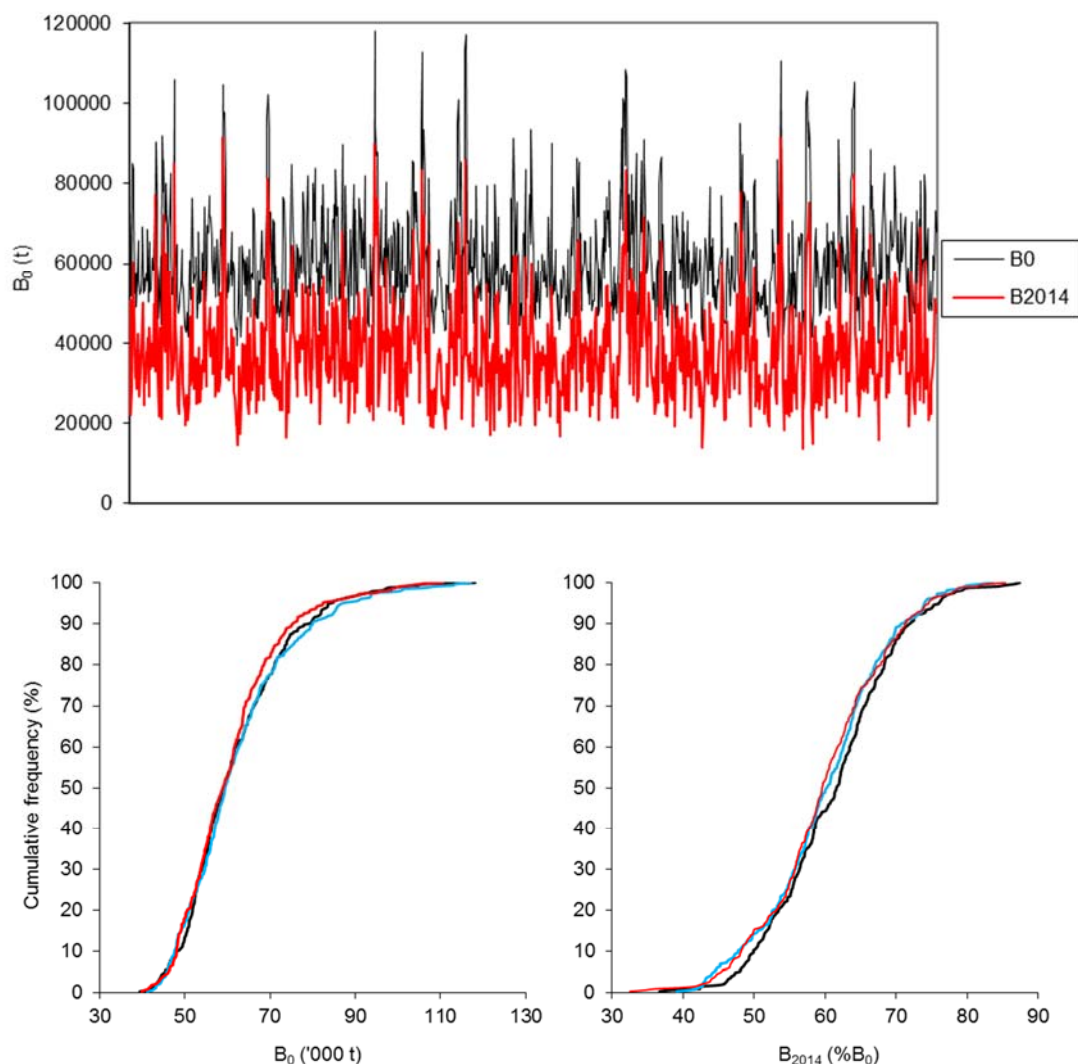

Figure 20: Trace diagnostic plot of the MCMC chains for estimates of B_0 and B_{2014} for the base model run (upper panel). MCMC diagnostic plots showing the cumulative frequencies of B_0 and B_{2014} (%B_0) for the first (black line), middle (blue line), and last (red line) third of the MCMC chain for the base model (lower panel).

Table 13: Bayesian median and 95% credible intervals of B_0, B_{2014}, and B_{2014} as a percentage of B_0 for all model runs.

Model run	B_0		B_{2014}		B_{2014} (%B_0)
Base	59 290	(44 040–94 040)	37 990	(19 740–70 310)	60.4 (43.6–77.6)
Half N_{eff}	50 120	(39 340–77 510)	27 910	(14 890–55 840)	55.4 (37.2–77.5)
Estimate *M*	65 610	(47 940–105 840)	44 900	(25 500–84 370)	67.8 (49.9–89.1)
Fixed *M*	60 270	(46 210–99 970)	33 620	(19 170–67 160)	54.9 (39.8–72.5)
CPUE	79 580	(59 330–102 310)	60 980	(38 140–86 890)	76.2 (62.5–87.0)
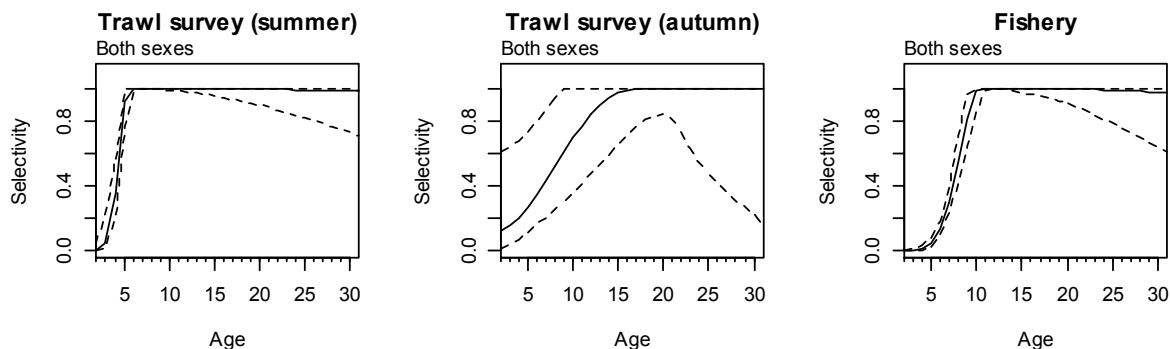
Figure 21: Base model — Estimated median selectivity ogive (with 95% credible intervals shown as dashed lines) for the trawl surveys and the trawl fishery.
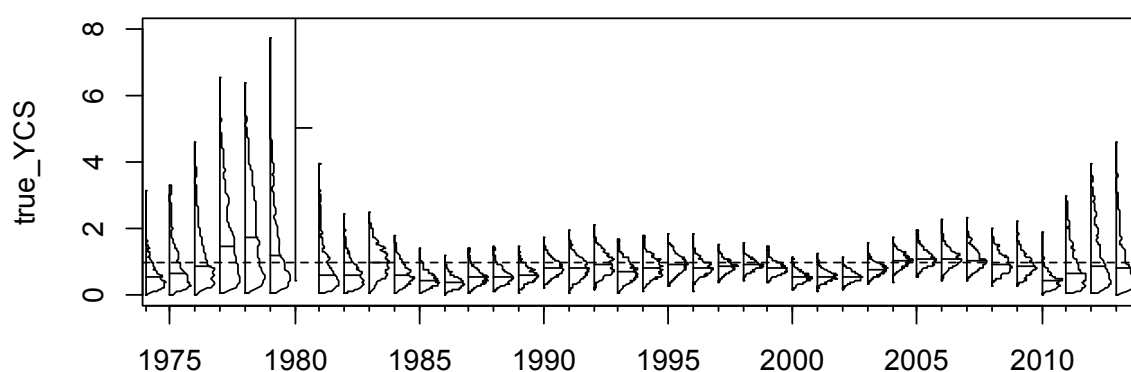
Figure 22: Base model — Estimated posterior distributions of year class strengths. The dashed horizontal line indicates the year class strength of one. Individual distributions are the marginal posteriors, with horizontal lines indicating the median.
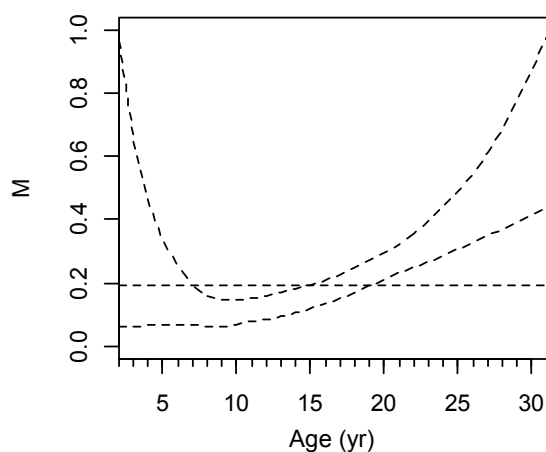

Figure 23: Base model — Estimated median natural mortality (M) ogive (with 95% credible intervals shown as dashed lines) for both sexes combined. The horizontal dashed line is at 0.19, the value that has been used as a fixed value for *M* in previous single sex assessments.
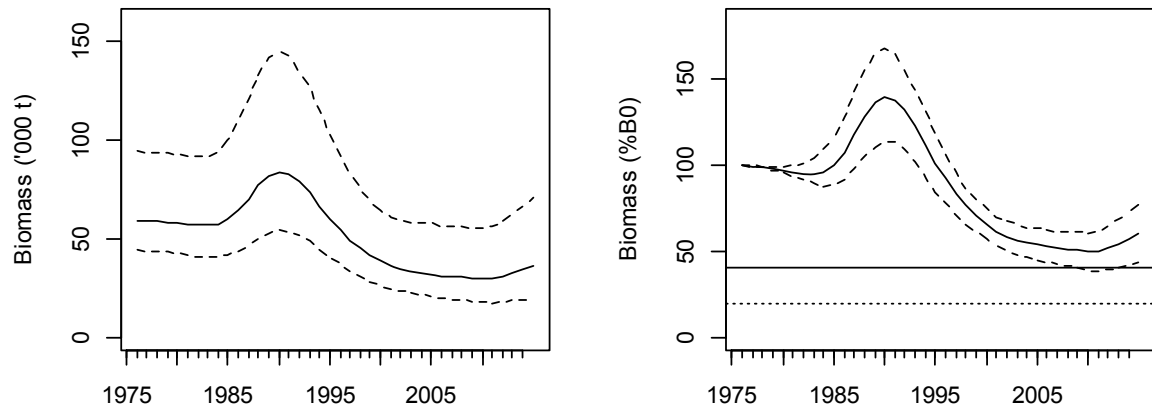
Figure 24: Base model — Estimated median trajectories (with 95% credible intervals shown as dashed lines) for absolute biomass and biomass as a percentage of B₀. Horizontal lines on the right panel indicate the Harvest Strategy Standard target (40% B₀, solid line) and soft limit (20% B₀, dotted line) levels.
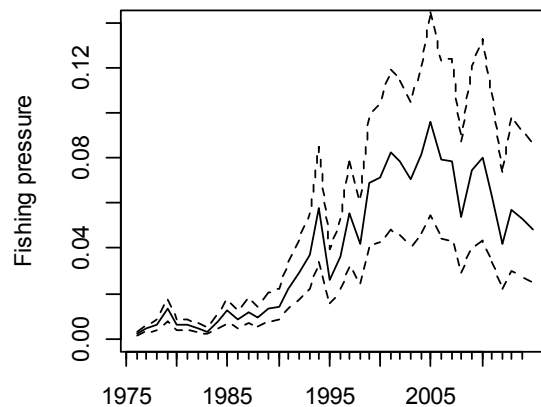
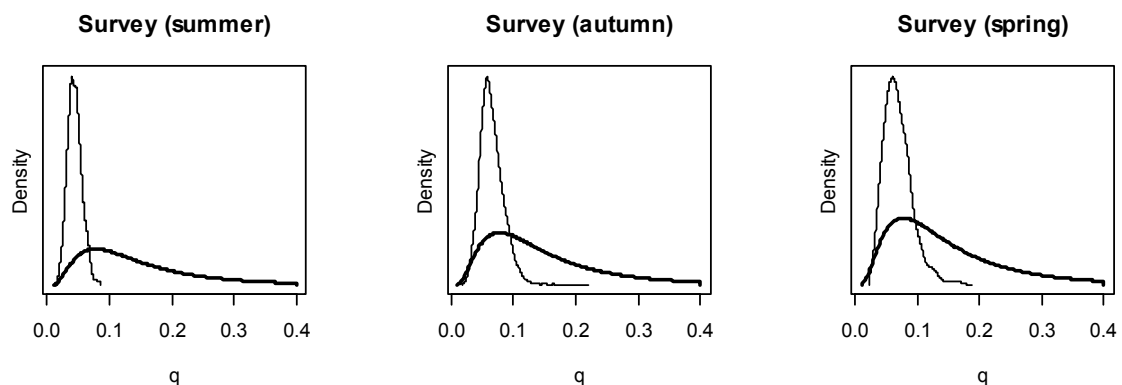**Figure 25: Base model — Estimated median trajectory of exploitation rate.**

Figure 26: Base model — Estimated posterior distribution (thin line) and prior (thick line) of survey catchability constants (*q*) for the three resource survey series.

The first sensitivity run investigated the effect of down-weighting the catch-at-age data by halving the effective sample sizes of all the input series (Half N$_{eff}$ model). This produced effective samples sizes for trawl survey samples ranging from 6 to 30, and from 5 to 42 for trawl fishery samples. Estimates of biomass, both virgin and current, were lower than for the base run, and stock status was more pessimistic (Table 13). Year class strength estimates were little different to the base case, but the selectivity of very

young fish increased for both trawl surveys and became unacceptably high for the summer series (Figure 27). The *M* ogive was shifted to the left resulting in a minimum *M* at age 5 and levels of *M* for very young fish that are unrealistically low (Figure 28). The results from this model are less believable than those from the base model.
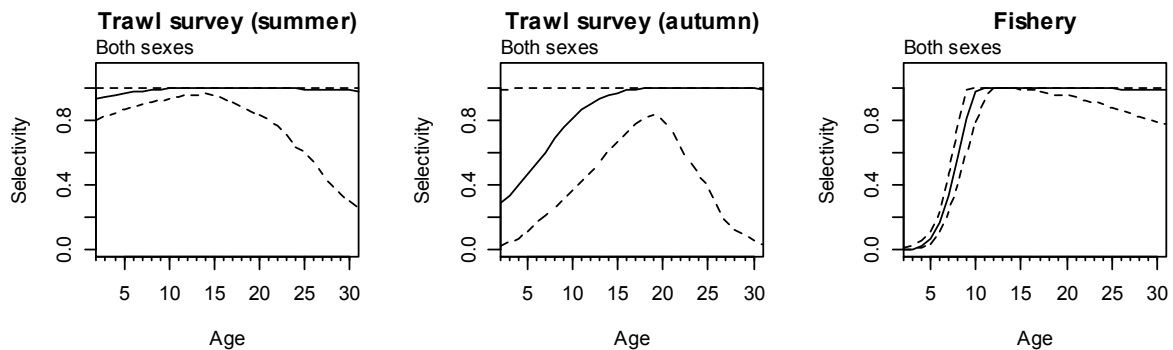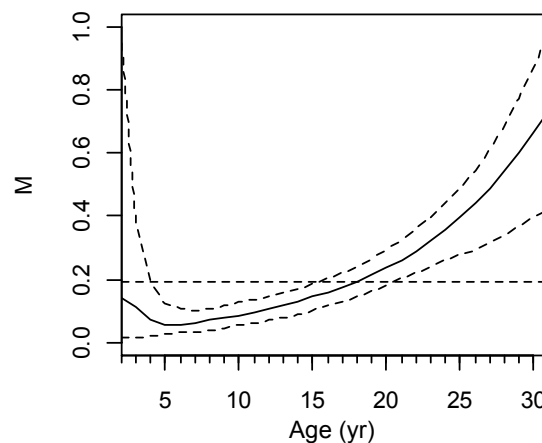

Figure 27: Half N_eff model — Estimated median selectivity ogive (with 95% credible intervals shown as dashed lines) for the trawl surveys and the trawl fishery.

Figure 28: Half N_eff model — Estimated median natural mortality (M) ogive (with 95% credible intervals shown as dashed lines) for both sexes combined. The horizontal dashed line is at 0.19, the value that has been used as a fixed value for *M* in previous single sex assessments.

The base model estimates *M* as an age-dependent ogive. Additional sensitivity runs investigated the influence of estimating *M* as a constant (Estimate *M* model), and fixing *M* at 0.18 for females and 0.20 for males (Fixed *M* model). The estimated constant *M* had a median of about 0.23 (Figure 29). Estimates of biomass, both virgin and current, were higher than for the base run, and stock status was more optimistic (Table 13). The shape of the biomass trajectory, and the pattern of year class strengths were little different to the base model. Selectivity ogives for the trawl fishery and the autumn survey series were also little different to those from the base model, but the summer survey series ogive was shifted markedly to the right, resulting in full selectivity not occurring until age 16 years (Figure 30). This is higher than for the trawl fishery, and is unrealistic given the smaller codend mesh used in the trawl surveys. Although *M* was estimated as a constant, all the selectivity ogives were still essentially logistic-shaped despite being parameterised as double-normal. It is disappointing that despite there being considerable catch-at-age data from the summer survey series, the selectivity ogive for the survey can be altered markedly when the method to estimate *M* is changed.
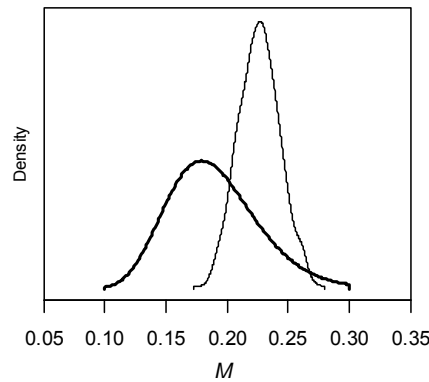
Figure 29: Estimate *M* model — Estimated posterior distribution (thin line) and prior (thick line) of instantaneous natural mortality (*M*).
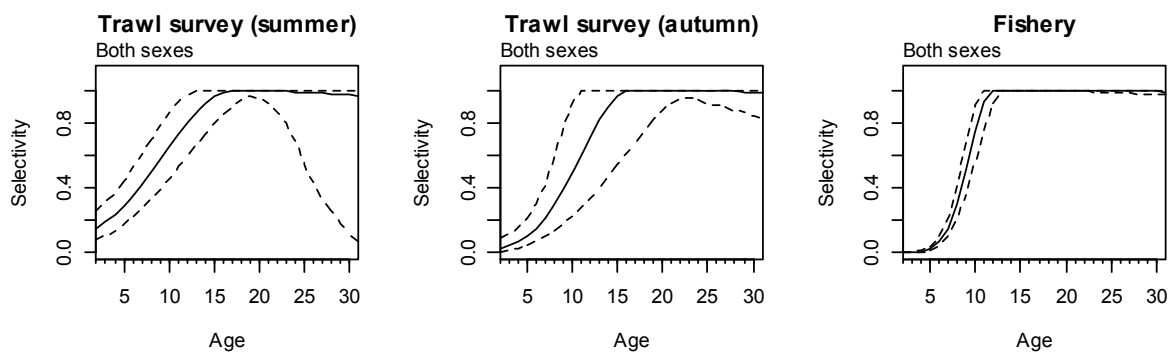

Figure 30: Estimate *M* model — Estimated median selectivity ogive (with 95% credible intervals shown as dashed lines) for the trawl surveys and the trawl fishery.

A sensitivity run where *M* was fixed at 0.18 for females and 0.20 for males produced little change in estimated virgin biomass relative to the base model, but current biomass was lower and stock status was more pessimistic (Table 13). Estimated selectivity ogives were little different to those from the base model — only the selectivities for the (relatively rare) oldest fish were noticeably different, being slightly lower (Figure 31). The lower current biomass estimate (relative to the base model) was associated with lower estimates of year class strengths throughout the 2000s (Figure 32).
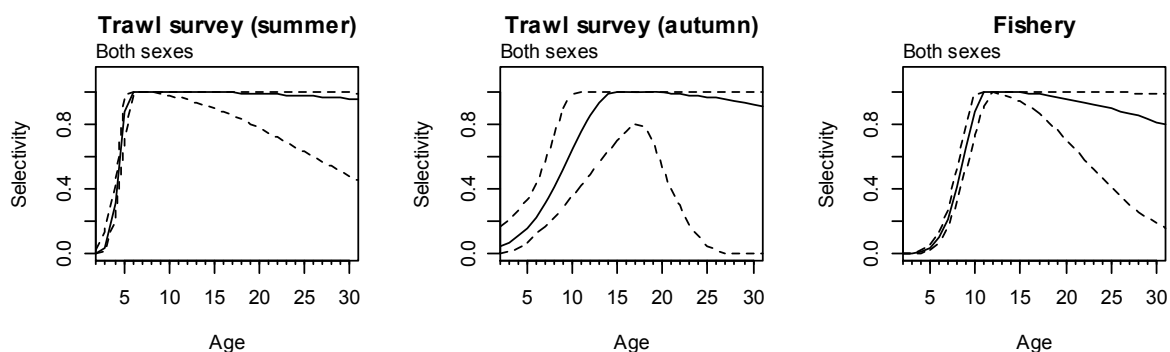

Figure 31: Fixed *M* model — Estimated median selectivity ogive (with 95% credible intervals shown as dashed lines) for the trawl surveys and the trawl fishery.
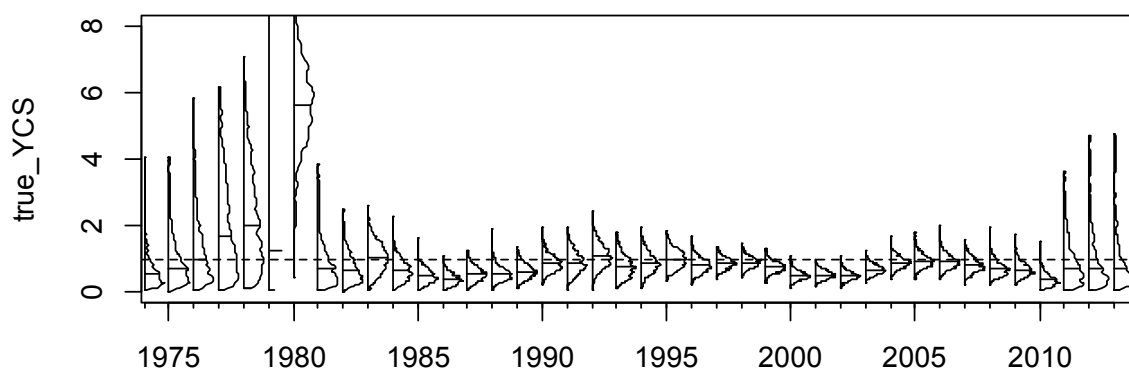
Figure 32: Fixed *M* model — Estimated posterior distributions of year class strengths. The dashed horizontal line indicates the year class strength of one. Individual distributions are the marginal posteriors, with horizontal lines indicating the median.

Adding the CPUE series to the base model produced higher estimates of absolute biomass (both virgin and current) and also stock status, i.e., 76% of B_0, compared to 60% for the base model (Table 13). The CPUE series is relatively flat (see Figure 13), so is has the effect of flattening the biomass trajectory (particularly the latter part), and hence, improving current stock status (Figure 33). A consequence of the overall flattening of the biomass trajectory is that the earlier year classes are estimated to be weaker and the later ones are stronger (Figure 34). The selectivity ogives are little different to those estimated in the base model. Exploitation rates (catch over vulnerable biomass) were estimated to have never been greater than 0.06 yr^{-1}. The estimates of trawl survey catchability constants (i.e., 3%, 5% and 6% for the summer, autumn and spring survey series, respectively) are very low, somewhat inconsistent with the priors, and probably unrealistic.
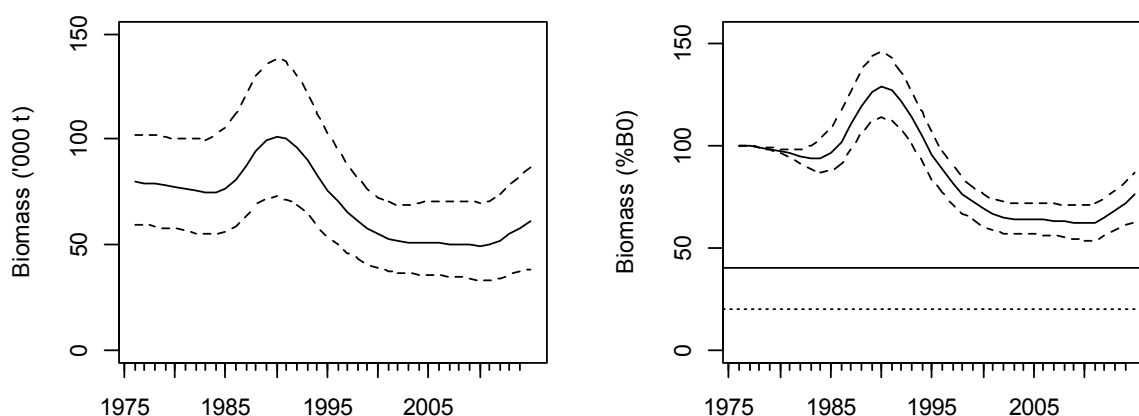

Figure 33: CPUE model — Estimated median trajectories (with 95% credible intervals shown as dashed lines) for absolute biomass and biomass as a percentage of B_0. Horizontal lines on the right panel indicate the Harvest Strategy Standard target (40% B_0, solid line) and soft limit (20% B_0, dotted line) levels.
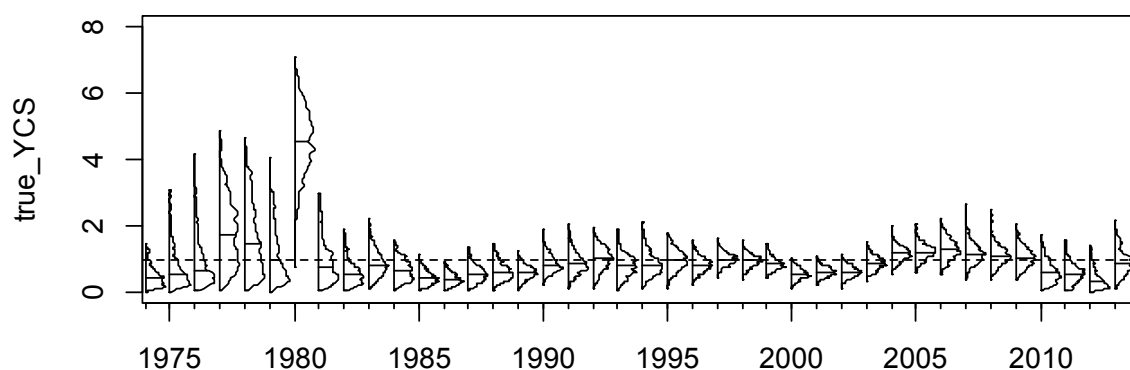
Figure 34: CPUE model — Estimated posterior distributions of year class strengths. The dashed horizontal line indicates the year class strength of one. Individual distributions are the marginal posteriors, with horizontal lines indicating the median.

5.1 Biomass projections

Biomass projections from the five models investigated using MCMC estimation were made assuming future annual catches of 2000 t from 2015 to 2019. This catch is the average from 2008 to 2013, and is slightly lower than the average annual catch since 1990 (2400 t). There is no specific TACC for the Sub-Antarctic stock. The HAK 1 administrative stock (with a TACC of 3701 t) includes all of the Sub-Antarctic, the western end of the Chatham Rise, and all around the North Island.

Year class strengths from 2011 onwards were selected randomly from the previously estimated year class strengths from 1997 to 2009.

Projections from all the models suggested that biomass will remain the same or increase slightly by up to 7% of B_0 between 2014 and 2019 (Table 14, Figure 35). The most pessimistic of these models suggests that there is little chance that biomass in 2019 will be lower than 35% of B_0. However, these projections are quite uncertain as indicated by the spreading confidence intervals after 2014 (Figure 35).

Table 14: Bayesian median and 95% credible intervals of projected B_{2019}, B_{2019} as a percentage of B_0, and B_{2019}/B_{2014} (%) for all model runs, with future annual catch equal to the mean from 2008 to 2013.

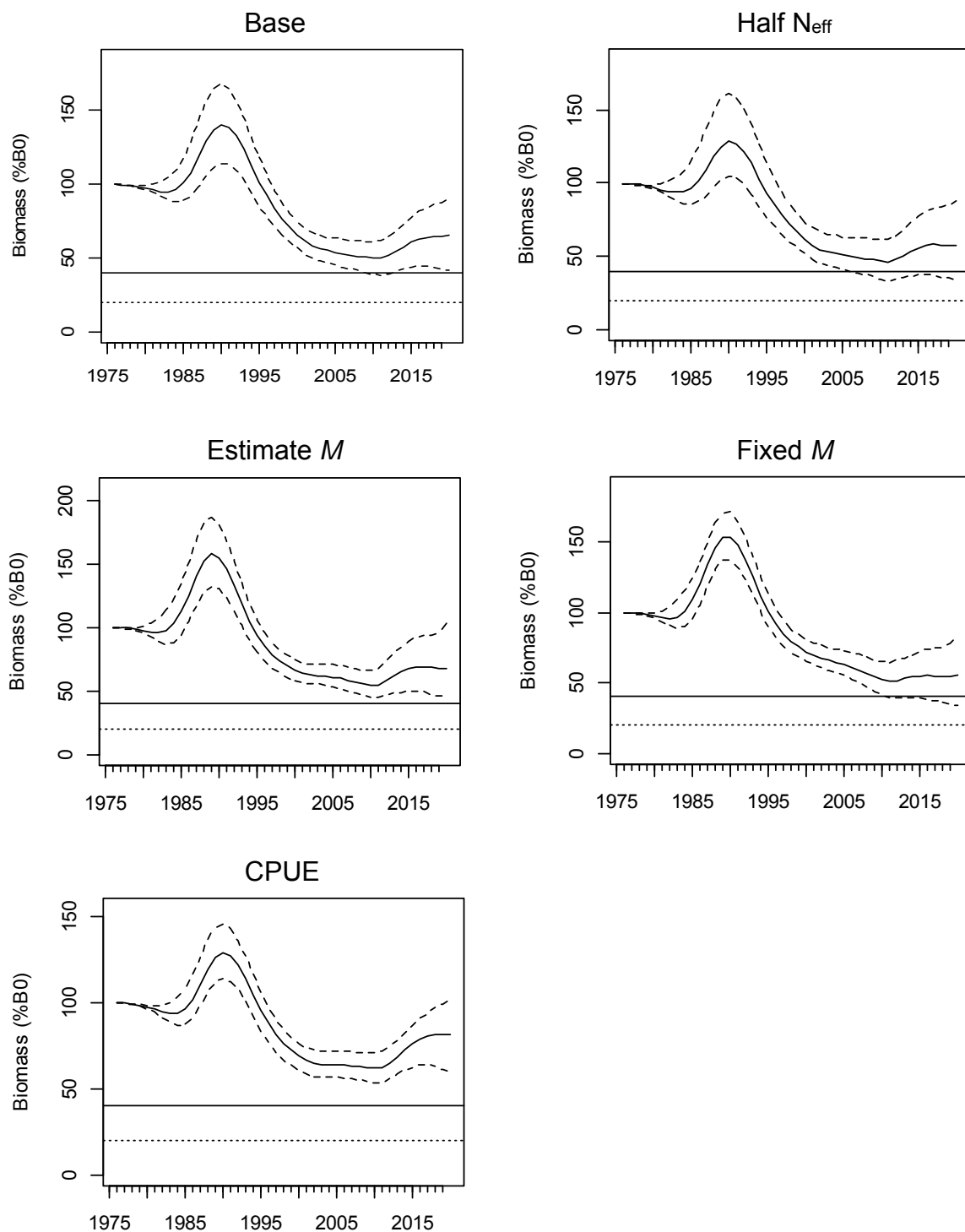| Model run	Future catch (t)	B_{2019}	B_{2019} (%B_0)	B_{2019}/B_{2014} (%)
Base	2 000	39 560 (19 760–79 890)	65.5 (41.8–90.5)	107 (87–135)
Half N_{eff}	2 000	29 290 (14 130–62 070)	57.7 (34.3–87.4)	103 (80–133)
Estimate M	2 000	45 420 (23 550–89 220)	68.0 (46.0–102.6)	99 (79–139)
Fixed M	2 000	33 680 (16 950–75 050)	55.1 (34.5–83.8)	100 (77–140)
CPUE	2 000	66 350 (36 280–95 320)	81.8 (59.3–101.8)	107 (88–129)

Figure 35: Estimated median trajectories (with 95% credible intervals shown as dashed lines) for biomass as a percentage of B_0, projected to 2019 with future catches assumed to be 2000 t annually, for all models. Horizontal lines on the right panel indicate the Harvest Strategy Standard target (40% B_0, solid line) and soft limit (20% B_0, dotted line) levels.

5.2 Management biomass targets

Probabilities that current and projected biomass will drop below default management reference points from the Harvest Strategy Standard (i.e., target, $40\%B_0$; soft limit, $20\%B_0$; hard limit, $10\%B_0$) are shown for all five models in Table 15. It appears extremely unlikely (i.e., less than 1%) that B_{2019} will be lower than the soft limit of $20\%B_0$, or very unlikely (less than 9%) to be below the target of $40\%B_0$.

Table 15: Probabilities that current (B_{2014}) and projected (B_{2019}) biomass will be less than 40%, 20% or 10% of B_0. Projected biomass probabilities are presented assuming a future annual catch of 2000 t.

Model run	Biomass	Management reference points		
		$40\% B_0$	$20\% B_0$	$10\% B_0$
Base	B_{2014}	0.007	0.000	0.000
	B_{2019}, 2000 t catch	0.020	0.000	0.000
Half N_{eff}	B_{2014}	0.049	0.000	0.000
	B_{2019}, 2000 t catch	0.088	0.001	0.000
Estimate M	B_{2014}	0.001	0.000	0.000
	B_{2019}, 2000 t catch	0.006	0.000	0.000
Fixed M	B_{2014}	0.027	0.000	0.000
	B_{2019}, 2000 t catch	0.083	0.000	0.000
CPUE	B_{2014}	0.000	0.000	0.000
	B_{2019}, 2000 t catch	0.000	0.000	0.000

6. DISCUSSION

This document updates the assessment of the Sub-Antarctic hake last reported by Horn (2013a). Past assessments of this stock have produced relatively uncertain results owing to the lack of strong contrast in the available series of relative abundance, i.e., two trawl survey series, and trawl CPUE (Dunn 2006, Horn 2008, 2013a). This problem still persists in the current assessment, but at least it is indicative of a stock that has not been markedly depleted by exploitation.

The previous assessment (Horn 2013a) showed that the sex ratios in commercial catches sampled by observers varied markedly between tows, trips, and years. A model without sex in the partition was deemed necessary to satisfactorily fit the commercial fishery proportion-at-age data, as it did not have to try to deal with conflicting information about changes in sex ratios over time and area. The current work further investigated this issue, primarily because productivity parameters vary markedly between male and female hake, so it was considered undesirable to remove sex from the partition. It was established that sex in or out of partition, and sexed or unsexed selectivity, had little impact on biomass or stock status. However, when selectivity was estimated by sex, the ogives varied markedly between sexes and so were unrealistic. Also, all models with sexed observations exhibited trends in the fits to these data (over time, and by sex). In addition, estimation of M in MPD runs had a significant impact on absolute biomass and produced the most believable trawl survey qs. Consequently, the Working Group concluded that the model that best avoided undesirable fitting trends and produced the most believable selectivity ogives and trawl survey qs was one with sex in the partition, but with unsexed observations, unsexed selectivity, and estimation of age-dependent M in the model. Impacts on this base model of down-weighting the catch-at-age data, fixing M, estimating M as a constant rather than an age-dependent ogive, and including the CPUE series were also investigated.

The base model estimated that the Sub-Antarctic spawning stock is currently at about 60% B_0, and that continued fishing at recent catch levels is likely to allow stock size to increase slightly in the next five years. Sensitivity model runs down-weighting the at-age data or varying M did not markedly alter the estimate of stock status (i.e., estimates ranged from 55 to 68% B_0). A sensitivity run including a trawl CPUE series did indicate a higher level of absolute biomass and a much more optimistic current stock

status. However, none of the model runs were indicative of current biomass being lower than 37% of B_0 (i.e., the most pessimistic 95% credible interval lower bound).

Estimated year class strengths often have quite wide 95% bounds, particularly at the start and the end of the estimated series. However, the median estimates suggest that variation in year class strength is not great for this stock; only three of the estimates from 1974 to 2013 are outside the range 0.5–2 (i.e., 1980 is much higher, and 1986 and 2010 are lower). A similar relatively low level of year class strength variation was estimated for the hake stocks on the Chatham Rise and WCSI (Horn 2013b). However, it is not possible to tell whether the low variability in year class strengths is correct (i.e., the actual variability is low) or is a consequence of uninformative data (e.g., the year-class signal in the at-age data could be poor either because these data are not representative of the catch, 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 recruitment driven by year class strength estimates. The research survey proportions-at-age distributions are collected systematically over time or space, but the fishery proportions-at-age are not. 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.

Information about absolute stock status of hake in the Sub-Antarctic is probably quite weak owing to the low level of contrast in all of the relative abundance series. Estimates of stock size and projected stock status are only slightly influenced by the shape of the selectivity ogives and the way in which M is included in the model. The age data are best fitted when M is estimated as an age-dependent ogive, but in all but the fixed M model the resource survey and fishery selectivity ogives were essentially logistic (even though they were parameterised as double-normal). When M was fixed, the very old fish are slightly less selected by the fishing gear (both in the surveys and the fishery). Such a situation where large, old fish are partially hidden from the fishing gear could occur in trawl surveys if these larger fish spend more time in midwater or on rough ground not able to be bottom trawled. However, the commercial fishery uses midwater trawls and so should have access to biomass 'hidden' from the resource surveys.

Estimates of resource survey catchability (qs) are very low in all model runs (i.e., 3–7%), particularly for the summer series, suggesting that the absolute catchability of the Sub-Antarctic trawl surveys is extremely low. It is not known if the catchability of the Sub-Antarctic trawl survey series is as low as estimated by the model, but hake are believed to be relatively more abundant over rough ground (that is likely to 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. Another plausible explanation for the low values is that there is little contrast in the biomass indices from the Sub-Antarctic trawl survey series, and that the model has little information on which to determine an appropriate "scale" of biomass estimates. Higher estimates of the relativity constant q (although confounded with selectivity) would likely result in lower current and virgin biomass estimates. A survey q of 9% was estimated using the same fishing gear to catch hake in a summer Chatham Rise survey (Horn 2013b). The assessment of that stock, fitting to a trawl biomass series with strong contrast, produced a very believable B_0 estimate of 37 000 t (Horn 2013b). That value, and the B_0 of 89 000 t estimated for the west coast South Island stock (Horn 2013b), provide tentative support for Sub-Antarctic virgin biomass to be in the range estimated from the five models described above (i.e., 50 000–80 000 t).

The assessment for Sub-Antarctic hake has been updated, and is indicative of a stock that has declined throughout the 1990s, but is still very likely to be above 50% of B_0. The decline is most likely to be a result of poor recruitment rather than fishing pressure. An annual catch in the range of 2000–3000 t appears very likely to be sustainable in the medium term at least. The stock is probably being reasonably

well monitored by the November-December trawl survey series. While the stock status appears to be reasonably well defined, estimates of past and current absolute stock size are very uncertain owing to a lack of contrast in the relative abundance series.

7. ACKNOWLEDGEMENTS

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APPENDIX A: Resource survey biomass indices for hake in HAK 1

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
Wesermünde	Mar–May 1979		–	[1]	–	–	Kerstan & Sahrhage 1980
Wesermünde	Oct–Dec 1979		–	[1]	–	–	Kerstan & Sahrhage 1980
Shinkai Maru	Mar–Apr 1982	SHI8201	200–800		6 045	0.15	N.W. Bagley, NIWA, pers. comm.
Shinkai Maru	Oct–Nov 1983	SHI8303	200–800		11 282	0.22	N.W. Bagley, NIWA, pers. comm.
Amaltal Explorer	Oct–Nov 1989	AEX8902	200–800		2 660	0.21	Livingston & Schofield 1993
Amaltal Explorer	Jul–Aug 1990	AEX9001	300–800		4 343	0.19	Hurst & Schofield 1995
Amaltal Explorer	Nov–Dec 1990	AEX9002	300–800		2 460	0.16	N.W. Bagley, NIWA, pers. comm.
Tangaroa	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]	–	–	
Tangaroa	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]	–	–	
Tangaroa	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]	–	–	
Tangaroa	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]	–	–	
Tangaroa	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
Tangaroa	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]	–	–	
Tangaroa	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
Tangaroa	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
Tangaroa	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
Tangaroa	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
Tangaroa	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
Tangaroa	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
Tangaroa	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
Tangaroa	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
Tangaroa	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
Tangaroa	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
Tangaroa	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
Tangaroa	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
Tangaroa	Nov–Dec 2011	TAN1117	300–800	[3]	1 434	0.30	Bagley et al. 2013
			1991 area	[4]	1 885	0.20	Bagley et al. 2013
			1996 area	[7]	2 004	0.23	Bagley et al. 2013
Tangaroa	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

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 an 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 an 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.

APPENDIX B: MPD fits to the at-age data

The plots presented below show the MPD model fits (lines) to the observed at-age data (dots) from the trawl fishery and the research survey series, for models 2, 3, and 5 (see Table 10).

- Model 2: At-age data unsexed, selectivity unsexed
- Model 3: At-age data by sex, selectivity unsexed
- Model 5: At-age data by sex, selectivity by sex

The model year of each set of observations is given on each panel. For the trawl survey plots, the autumn survey dates are appended with "a" and the spring survey is appended with "s".
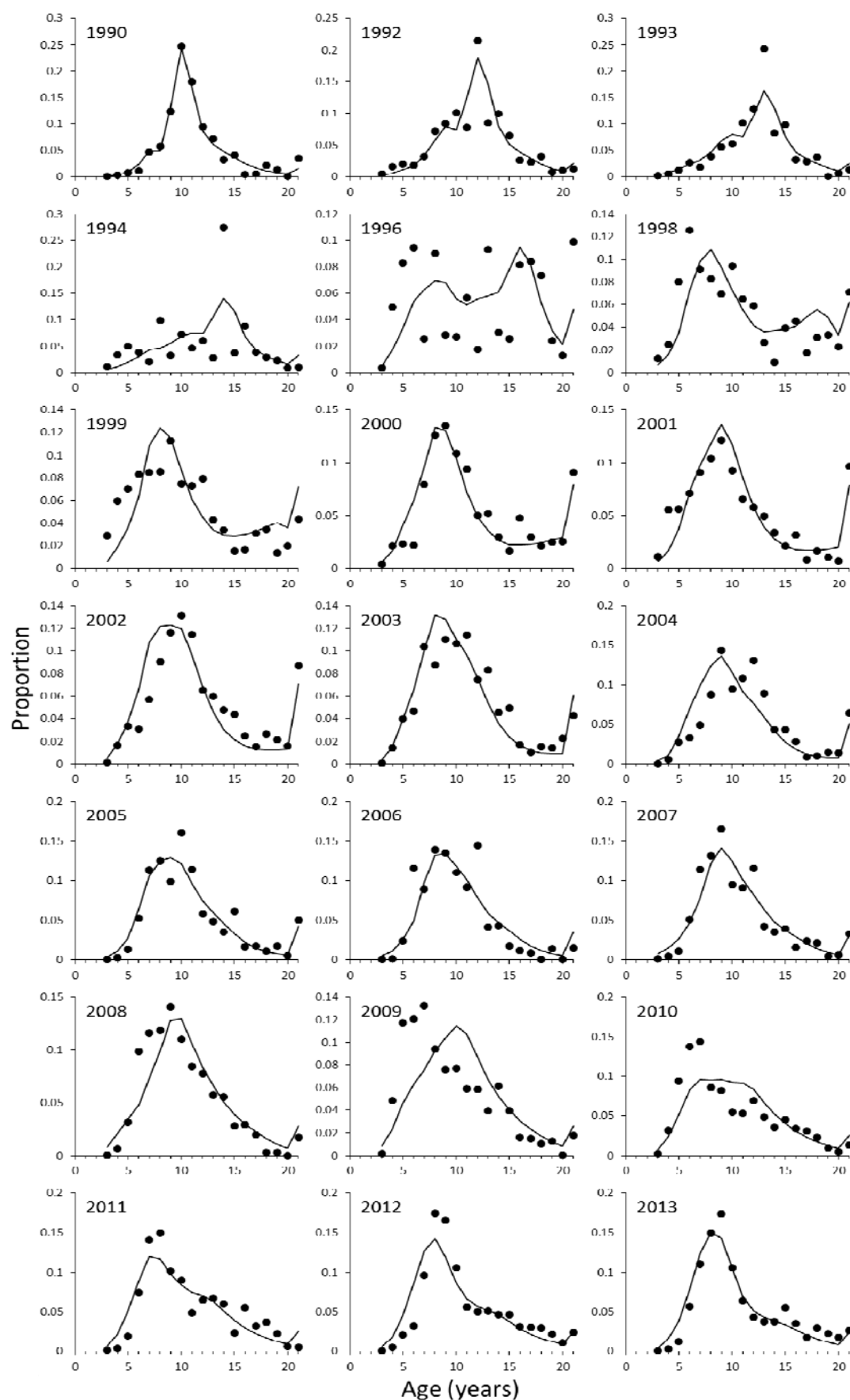
Figure B1: Model 2, trawl fishery, unsexed data, single selectivity.
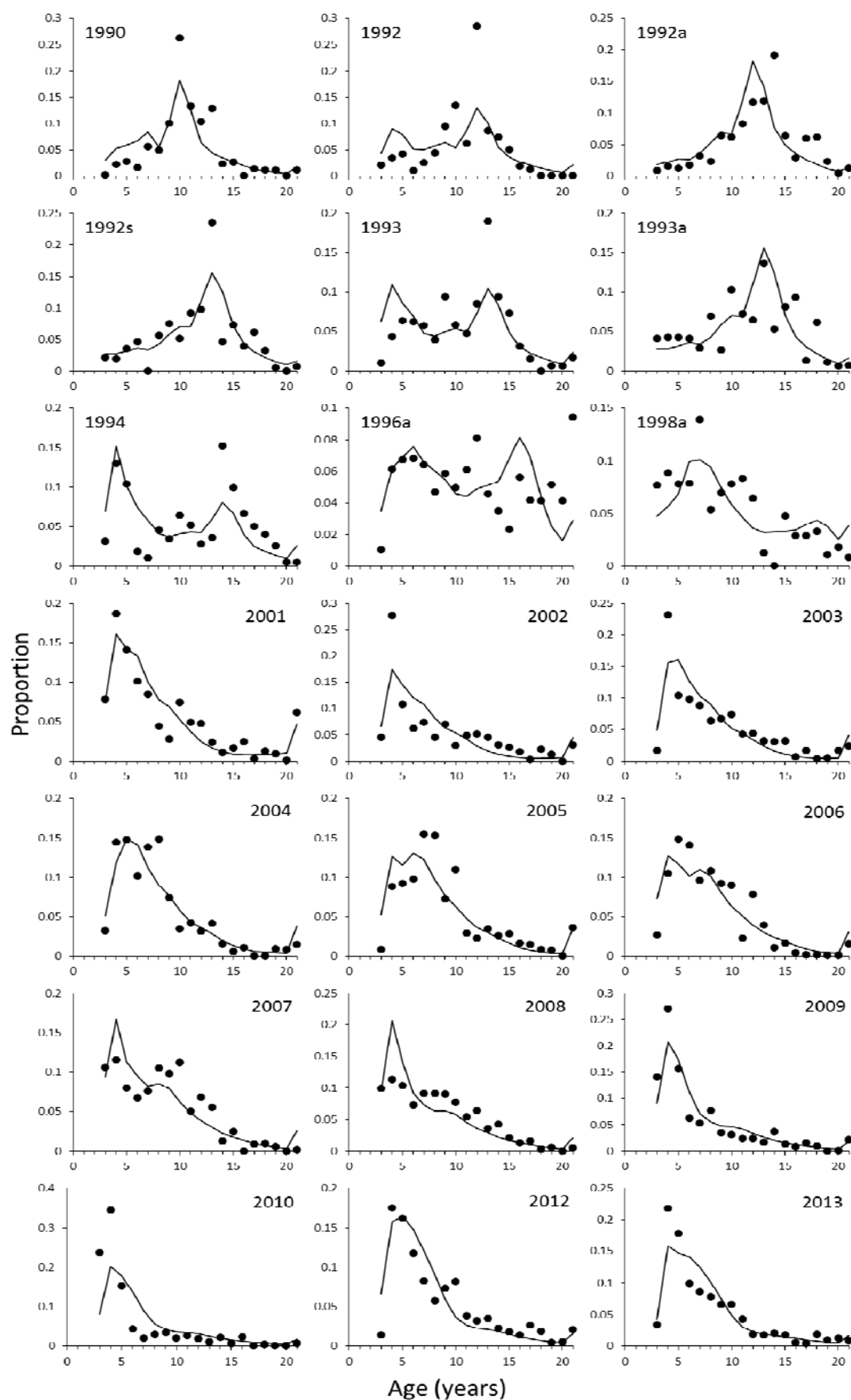
Figure B2: Model 2, trawl surveys, unsexed data, single selectivity.
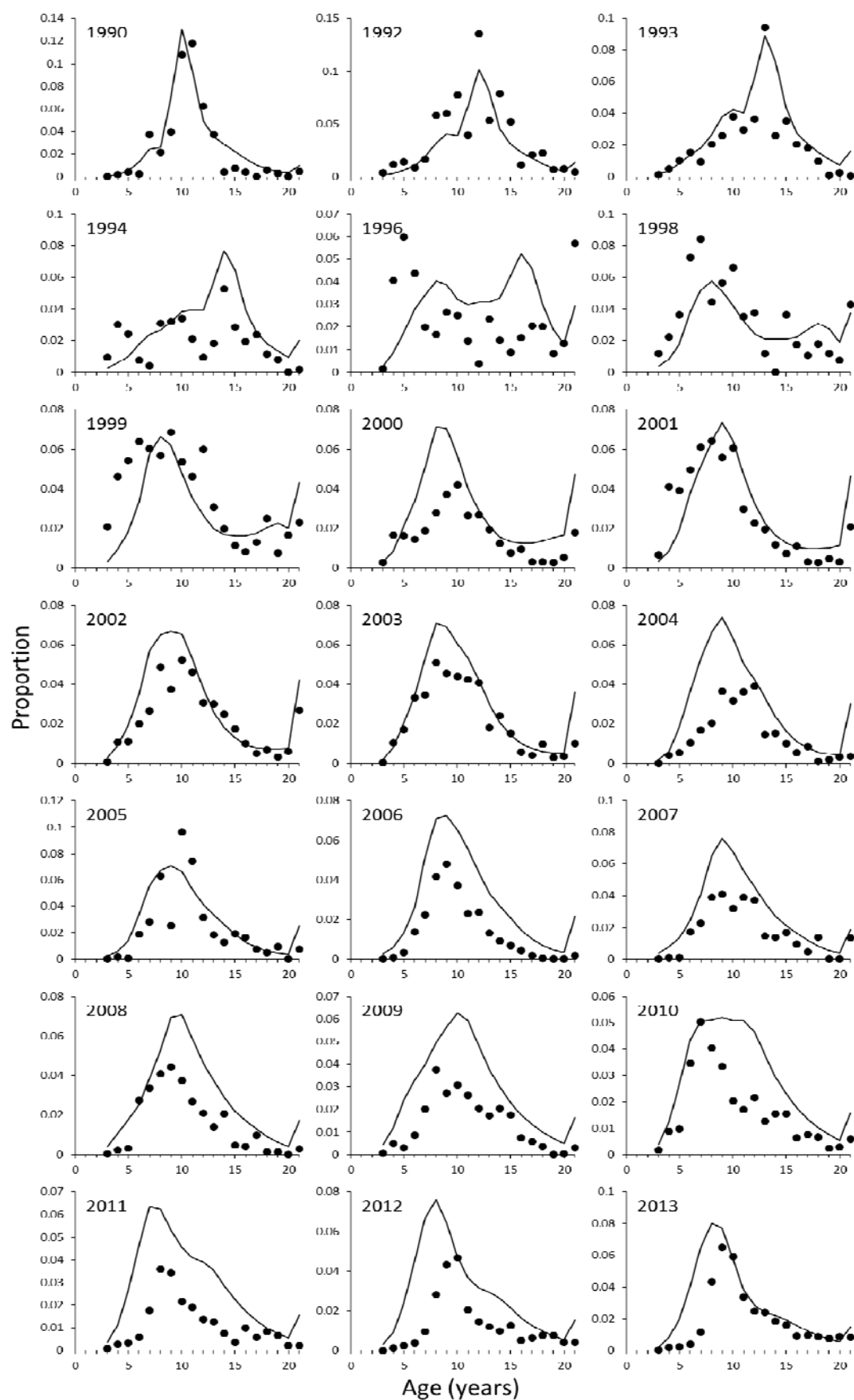
Figure B3: Model 3, trawl fishery, data by sex (female), single selectivity.
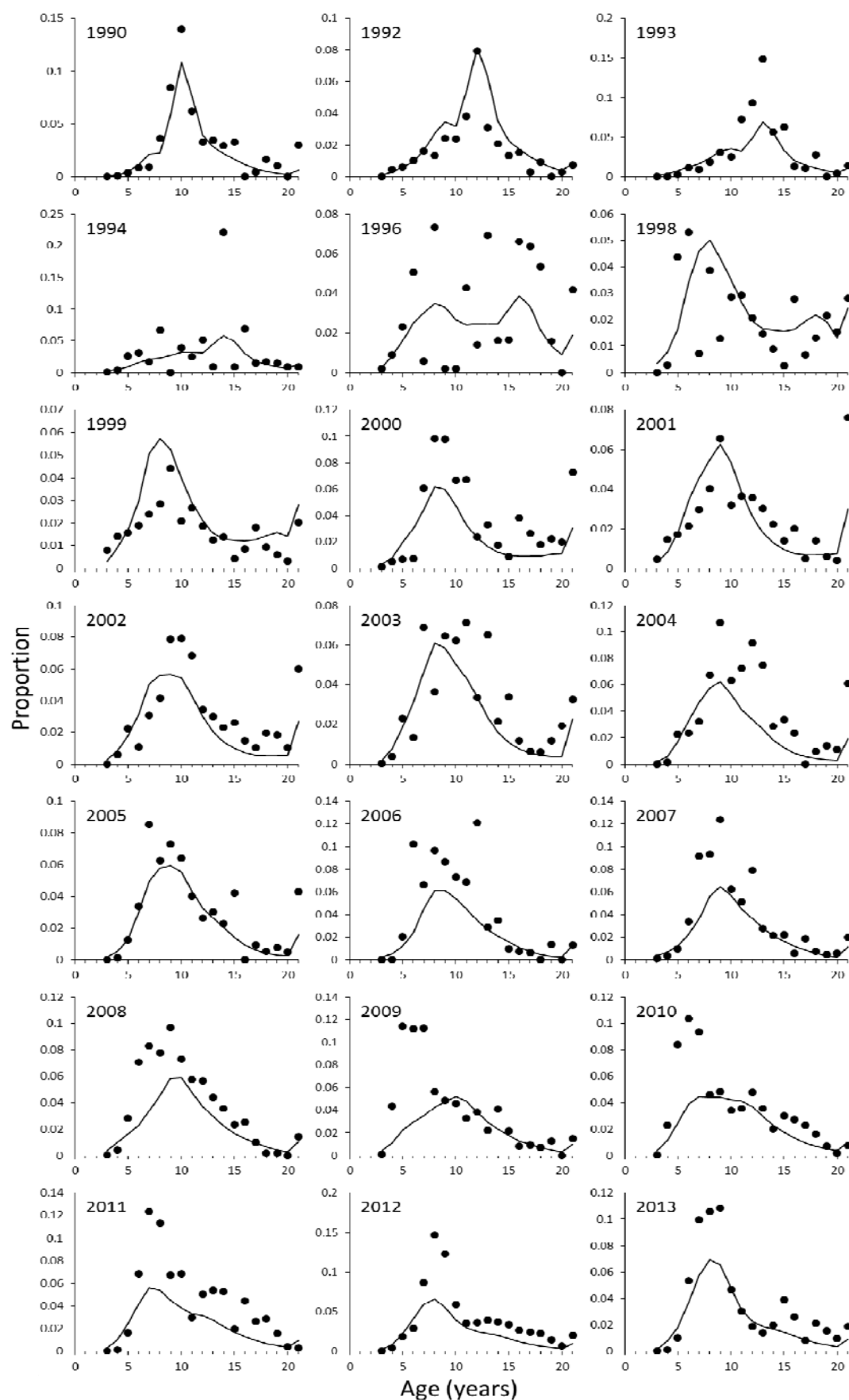
Figure B4: Model 3, trawl fishery, data by sex (male), single selectivity.
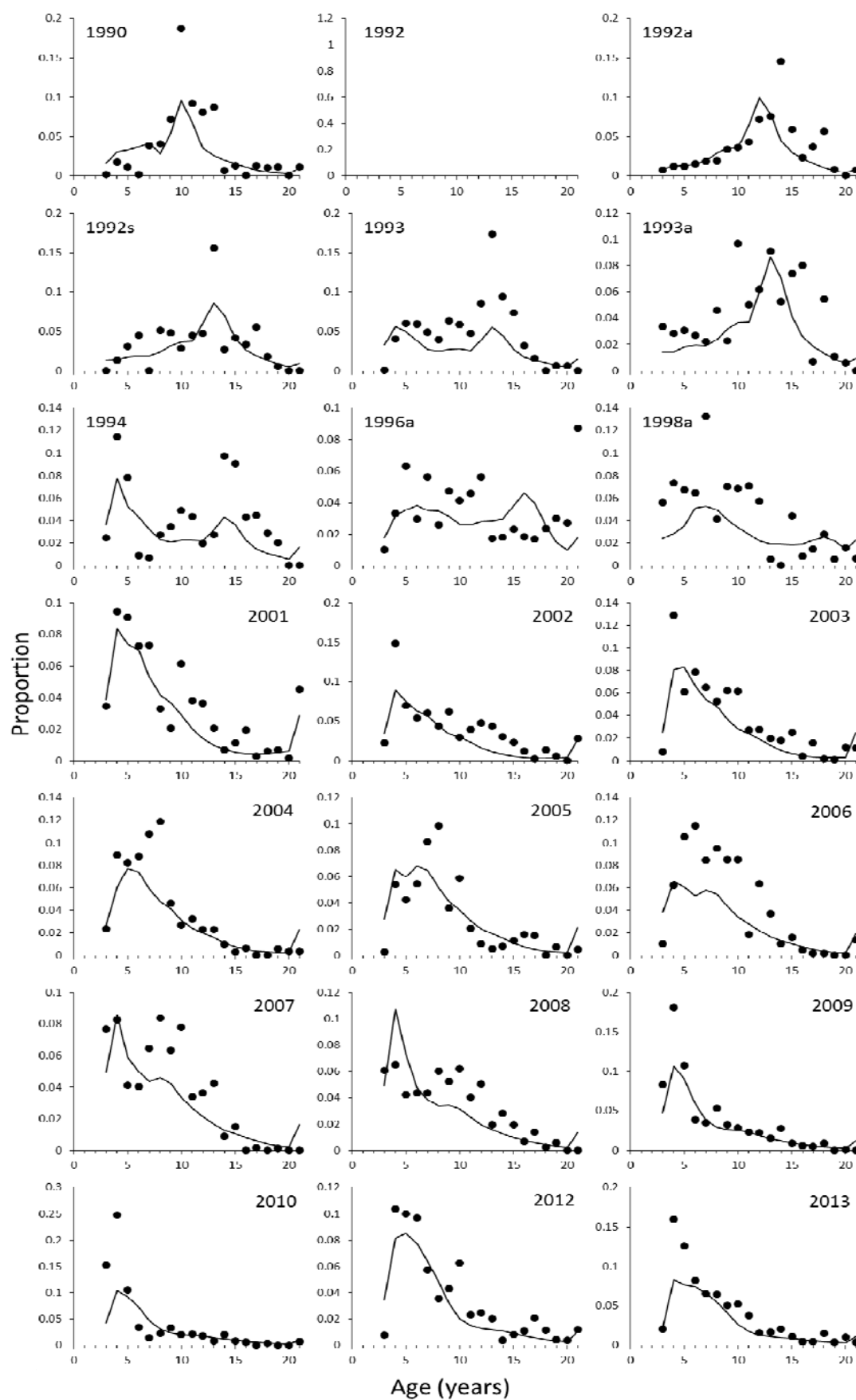
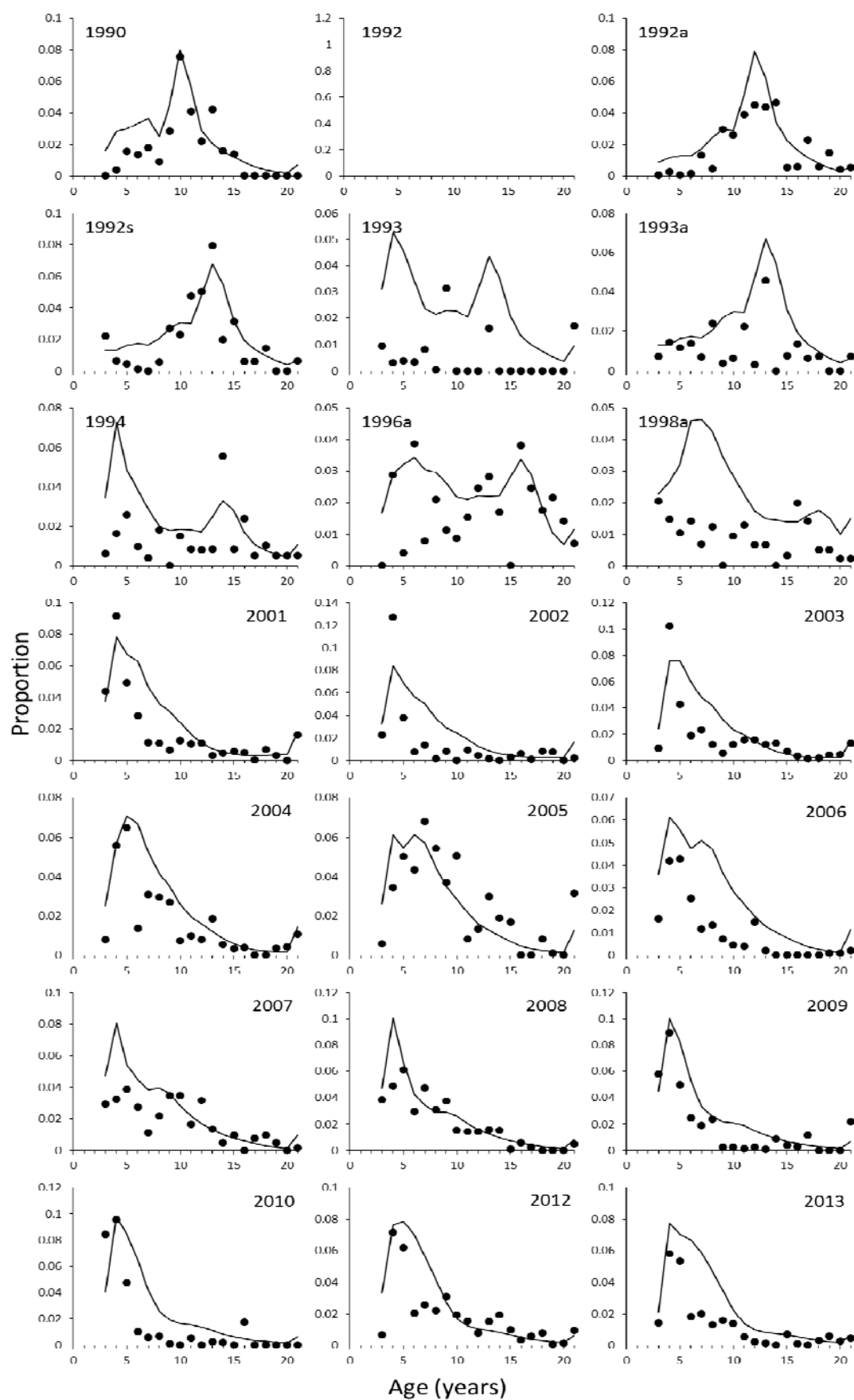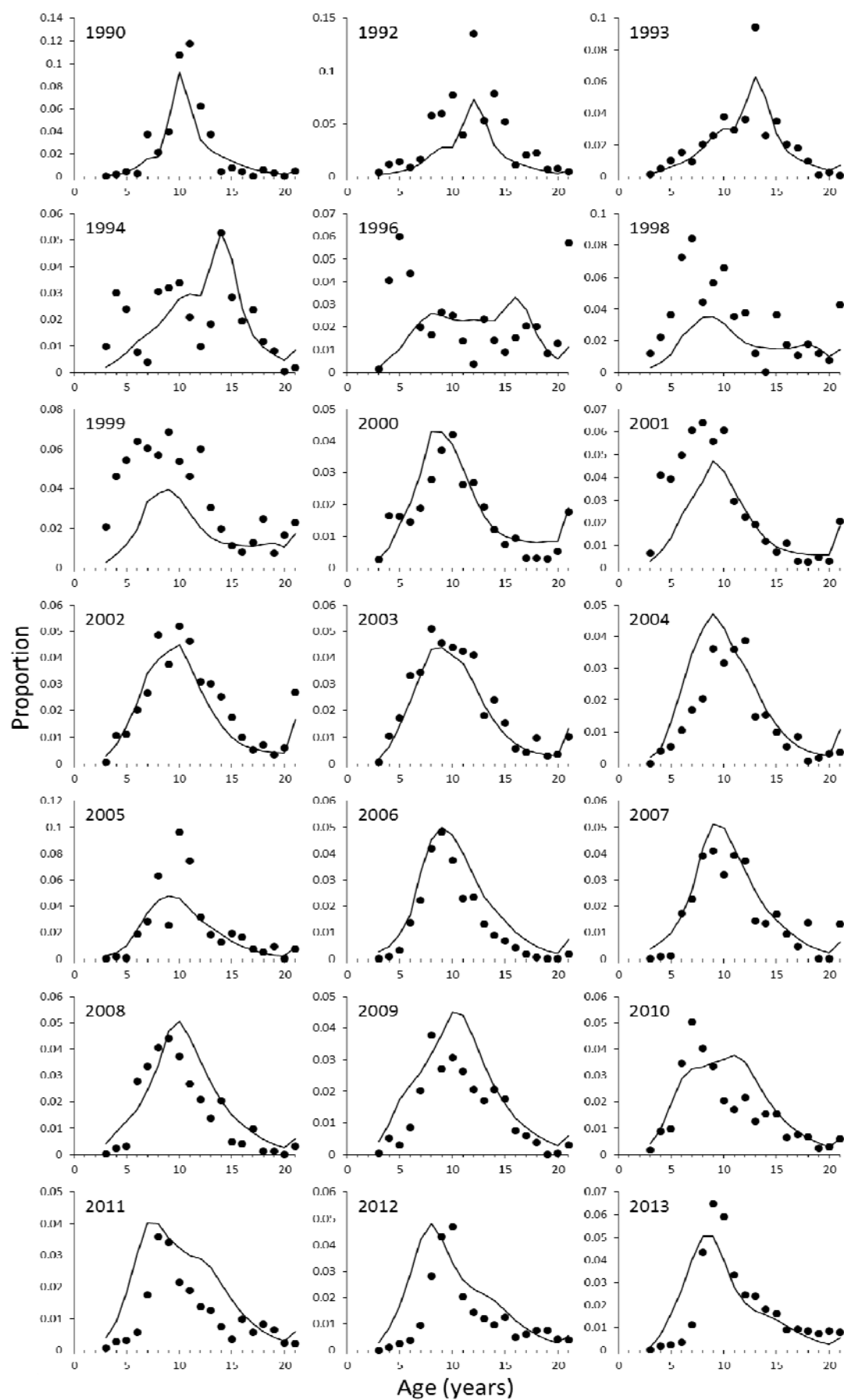**Figure B5: Model 3, trawl surveys, data by sex (female), single selectivity.**

Figure B6: Model 3, trawl surveys, data by sex (male), single selectivity.

Figure B7: Model 5, trawl fishery, data by sex (female), selectivity by sex.
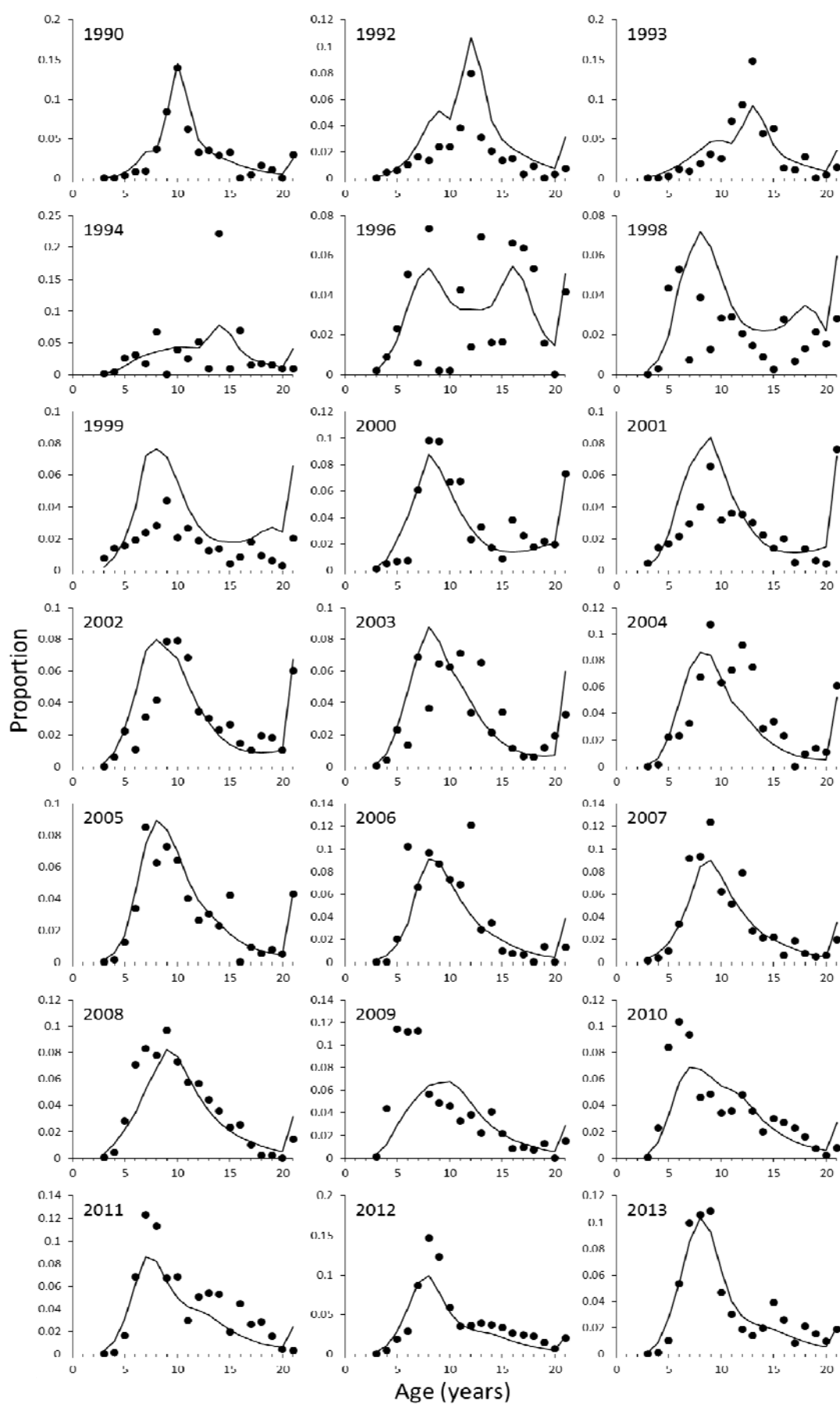
Figure B8: Model 5, trawl fishery, data by sex (male), selectivity by sex.
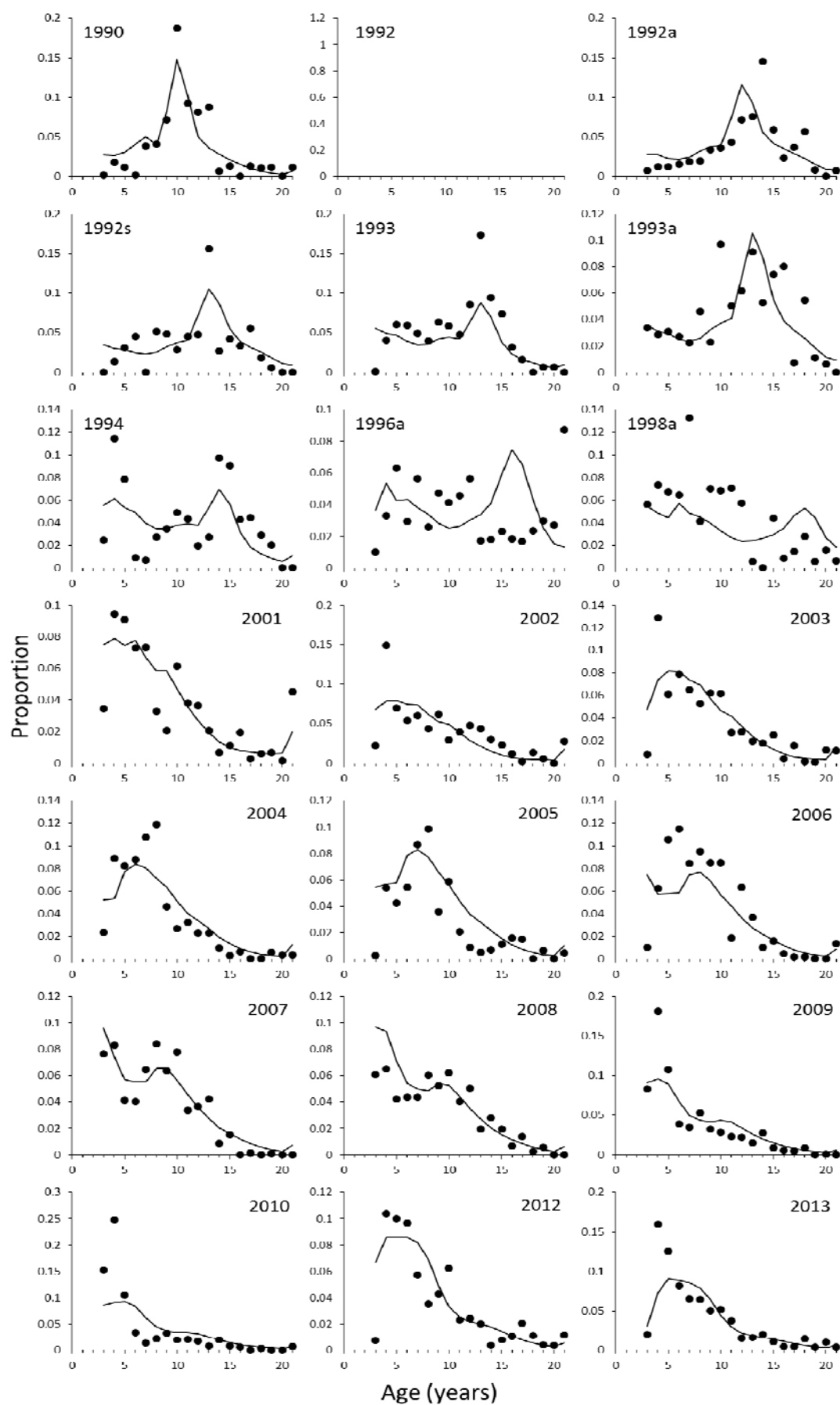
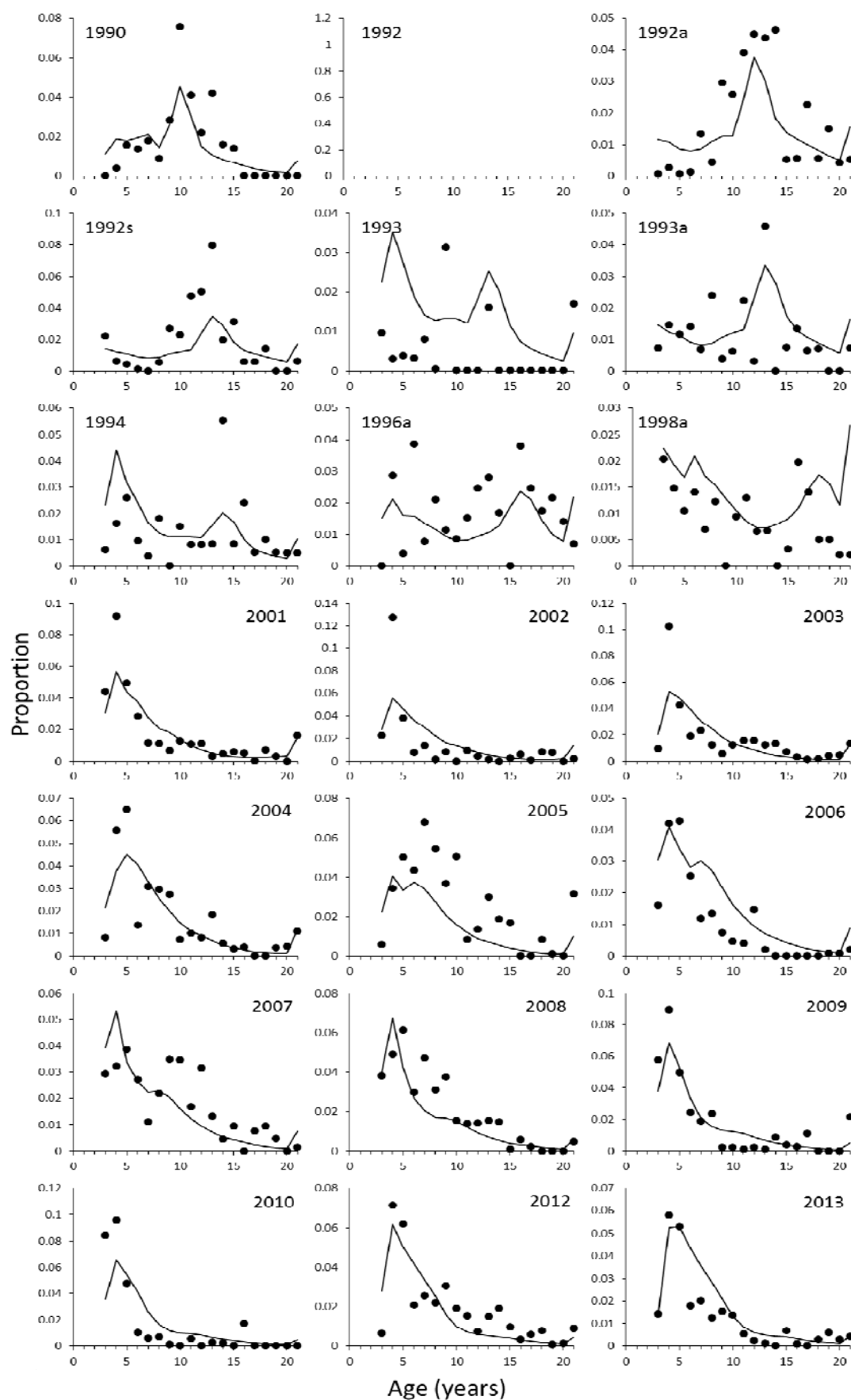**Figure B9: Model 5, trawl surveys, data by sex (female), selectivity by sex.**

Figure B10: Model 5, trawl surveys, data by sex (male), selectivity by sex.