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Descriptive analysis and model inputs for the 2022 stock assessment of hake (*Merluccius australis*) off the west coast South Island (HAK 7), to the 2020–21 fishing year

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

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EXECUTIVE SUMMARY

Dunn, A.[1]; Mormede, S.[2]; Webber, D.N.[3] (2023). Descriptive analysis and model inputs for the 2022 stock assessment of hake (*Merluccius australis*) off the west coast South Island (HAK 7), to the 2020–21 fishing year.

***New Zealand Fisheries Assessment Report 2023/44.* 56 p.**

Hake (*Merluccius australis*, HAK) is an important commercially caught species found throughout the middle depths of the New Zealand Exclusive Economic Zone (EEZ) south of 40° S and caught mainly by deepwater demersal trawls. Hake are managed in three Fishstocks: (i) the Challenger Fisheries Management Area (FMA) (HAK 7), (ii) the Chatham Rise FMA (HAK 4), and (iii) the remainder of the EEZ comprising the Auckland, Central, Southeast (Coast), Southland, and Sub-Antarctic FMAs (HAK 1). Hake are assessed as three main biological stocks: the west coast South Island, Chatham Rise, and Sub-Antarctic.

This report provides a characterisation of the hake stock and fishery in HAK 7 off the west coast of the South Island, including a description of the fishery and revised catch-per-unit-effort (CPUE) indices up to the end of the 2020–21 fishing year.

The west coast South Island fishery is concentrated in Statistical Area 034 in depths of 300–1000 m, off the west coast of the South Island. The total annual catch of hake in recent years has been declining, and HAK 7 catch halved over the last decade. Formerly, the fishery mostly caught hake in either target hoki or hake trawls, but, since about 2005, the fishery has changed with lower catches of hake taken as bycatch and fewer vessels operating in the area.

Spatial analyses of age and length data suggest that the pattern of sizes and ages seen in the population is consistent with a stock hypothesis that juvenile hake reside off the west coast South Island, with sub-adult or pre-mature fish dispersing widely across the Challenger Plateau, before returning as adults during the winter months to feed on migrating hoki and spawn.

The CPUE estimates of relative abundance indices by year were developed using a forward stepwise linear regression of both lognormal and binomial CPUE indices combined. The data used for the analysis consisted of catch and effort records from off the west coast South Island from vessels targeting hoki or hake and reporting the catch and effort on trawl catch, effort and processing returns or electronic reporting system trawl forms for tow-by-tow data. Estimated standardised CPUE indices had a different trend to the west coast South Island offshore trawl survey index and were more likely to reflect spatial temporal patterns in fish distribution and fishery operational patterns rather than changes in the abundance of hake.

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

1. INTRODUCTION

Hake (*Merluccius australis*) is an important commercially caught species found throughout the middle depths of the New Zealand Exclusive Economic Zone (EEZ) south of 40° S, typically in depths of 250–800 m (Hurst et al. 2000). Hake are caught mainly by deepwater demersal trawls, usually as bycatch in hoki (*Macruronus novaezelandiae*) target fisheries, with some caught by direct targeting (Ballara 2018).

The current management of hake divides the fishery into three Fishstocks: (i) the Challenger Fisheries Management Area (FMA) (HAK 7), (ii) the Chatham Rise FMA (HAK 4), and (iii) the remainder of the EEZ comprising the Auckland, Central, Southeast (Coast), Southland, and Sub-Antarctic FMAs (HAK 1). An administrative Fishstock (with no recorded landings) is also defined for the Kermadec FMA (HAK 10) (Fisheries New Zealand 2023). There are likely to be three main biological stocks of hake. These are the west coast of the South Island (HAK 7), the Chatham Rise (HAK 4 and the southern part of the northern regions of HAK 1), and the Sub-Antarctic (southern waters of HAK 1) (Fisheries New Zealand 2023). The Quota Management Areas (QMA) for hake and stock boundaries are shown in Figure 1.

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

The reported catch history of hake in each of the QMAs is given in Table 1 and Figure 2. In HAK 7, reported landings peaked at almost 10 000 t in 1995–96 and have since declined to under 1400 t in the most recent analysis year (Figure 2); the Total Allowable Commercial Catch (TACC) for hake was 7700 t until 2016–17, and was then reduced in two steps to 5064 t in 2017–18 and then 2272 t in 2019–20.

In the late 1990s and early 2000s, hake fishers misreported catches between QMAs, typically misreporting catches of hake from HAK 7 as catch from either HAK 1 or HAK 4. The reported catches of hake in each area were reviewed in 2002 and several suspect records identified. Dunn (2003a) provided revised estimates of the total landings by stock. Almost all the area misreporting was from HAK 7 (west coast South Island) to the Chatham Rise (HAK 4 and the part of HAK 1 on the Chatham Rise), with a small amount in the Sub-Antarctic area of HAK 1 (Dunn 2003a). Dunn (2003a) estimated that the level of hake over-reporting on the Chatham Rise (and hence under-reporting off the west coast South Island) was between 16 and 23% (700–1000 t annually) of landings between 1994–95 and 2000–01, mainly in June, July, and September. Probable levels of area misreporting prior to 1994–95 and between the west coast South Island and Sub-Antarctic were estimated as low (Dunn 2003a). There has been no evidence of similar area misreporting since 2001–02 (Ballara 2018). A revised catch history for hake, accounting for this misreporting, for each stock is given as Table 2.

Hake stocks have previously been assessed with stock assessments for at least one of the three stocks each year since 1991. Previous assessments of hake were in the 1991–92 (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 2004), 2004–05 (Dunn et al. 2006), 2005–06 (Dunn 2006), 2006–07 (Horn & Dunn 2007), 2007–08 (Horn 2008), 2009–10 (Horn & Francis 2010), 2010–11 (Horn 2011), 2011–12 (Horn 2013a), 2012–13 (Horn 2013b), 2014–15 (Horn 2015), 2016–17 (Horn 2017), 2017–18 (Dunn 2019), 2018–19 (Kienzle et al. 2019), 2019–20 (Holmes 2021), and 2020-21 fishing years (Dunn et al. 2021a). The most recent stock assessment was for west coast South Island hake for the 2021–22 fishing year and is described by Dunn et al. (2023).

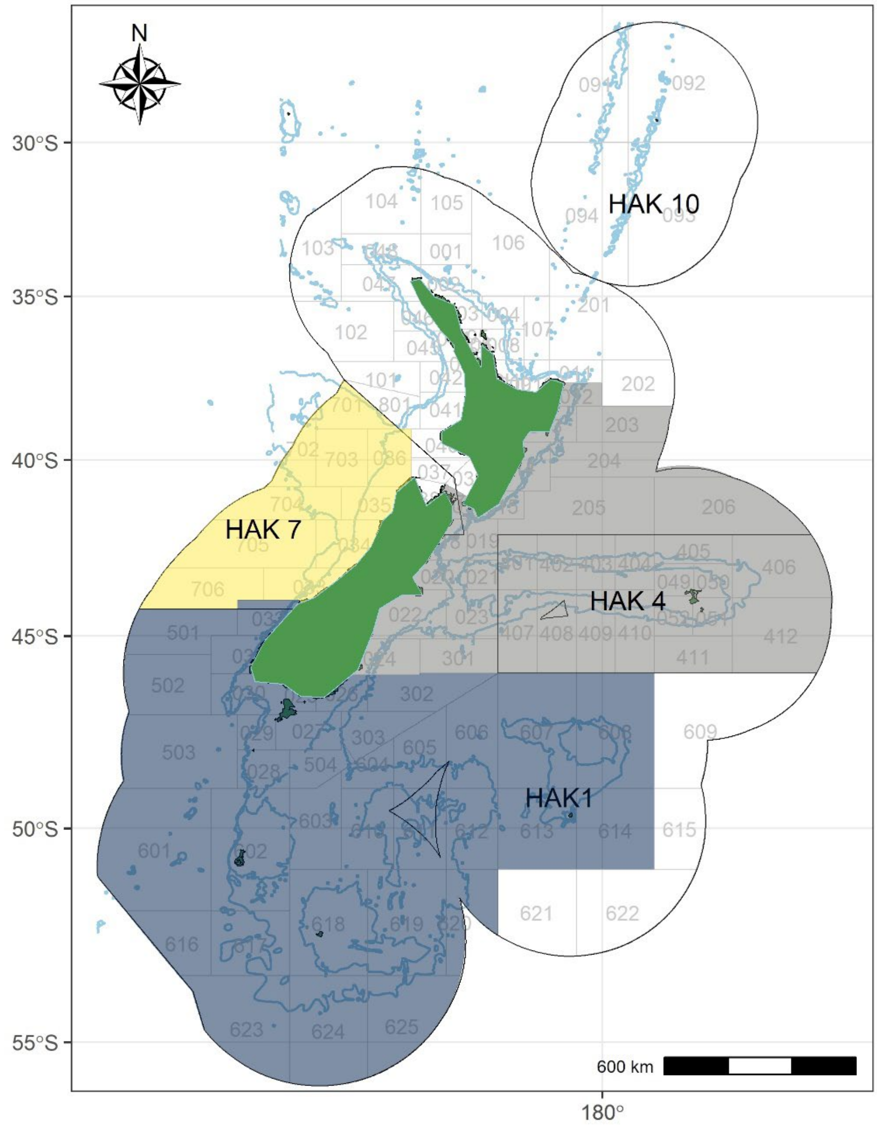

Figure 1: Quota Management Areas (QMAs) HAK 1, 4, 7, and 10 (black lines), statistical areas (grey), and hake biological stock boundaries: west coast South Island (yellow), Chatham Rise (light grey), and Sub-Antarctic (dark grey).

Commercial catch and effort data were first analysed to produce standardised catch-per-unit-effort (CPUE) indices for HAK 1 in 1998 (Kendrick 1998) and were updated, using the methodology of Gavaris (1980), by Vignaux (1994). Since then, CPUE abundance indices have been updated for hake using a similar methodology but have not often been used as a main abundance index in stock assessments. In 2012 and 2013, Ballara (2012, 2013) showed that the estimated tow-by-tow and daily summary CPUE indices had similar trends. More recently for the west coast South Island, Finucci (2019) updated the descriptive analyses of hake and estimates of CPUE abundance indices, including data up to the end of 2017–18.

Estimates of age frequencies from the commercial catch and from resource surveys are calculated under annual Fisheries New Zealand ageing projects that are reported elsewhere (e.g., Horn & Sutton 2019; Saunders et al. 2021; Ballara et al. 2022); however, they have not been summarised over the period of the west coast South Island fishery.

This report fulfils Specific Objective 1 of Project HAK2021-01. The overall Objective was "To carry out stock assessments of hake (*Merluccius australis*) off the west coast of the South Island (HAK 7) including estimating stock biomass and stock status" and Specific Objective 1 was "To carry out a descriptive analysis of the commercial catch and effort data for hake off the west coast of the South Island and update the standardised catch and effort analyses". This report provides a descriptive summary of catch and effort data since 1989–90, a summary of resource surveys, an update of biological parameters, and an update and revision of the analysis of the CPUE data for hake from the west coast South Island stock for the fishing years 1990–91 (1991) to 2020–21 (2021).

Table 1: Reported landings (t) of hake by Fishstock from 1983–84 to 2020–21 and actual total allowable commercial catches (TACCs) (t) for 1986–87 to 2021–22. Fisheries Statistics Unit (FSU) data from 1984–1986; QMS data from 1986 to the present (from Fisheries New Zealand 2023).

Fish stock	HAK 1		HAK 4		HAK 7		HAK 10			
FMA(s)	1, 2, 3, 5, 6, 8, 9		4		7		10		Total	
	Landings	TACC	Landings	TACC	Landings	TACC	Landings	TACC	Landings	TACC
1983–84 [1]	886	–	180	–	945	–	0	–	2 011	–
1984–85 [1]	670	–	399	–	965	–	0	–	2 034	–
1985–86 [1]	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	7 781	6 930
1990–91	2 603	2 610	743	1 000	6 148	3 310	0	10	9 494	6 930
1991–92	3 156	3 500	2 013	3 500	3 027	6 770	0	10	8 196	13 780
1992–93	3 525	3 501	2 546	3 500	7 154	6 835	0	10	13 225	13 846
1993–94	1 803	3 501	2 587	3 500	2 974	6 835	0	10	7 364	13 847
1994–95	2 572	3 632	3 369	3 500	8 841	6 855	0	10	14 782	13 997
1995–96	3 956	3 632	3 466	3 500	8 678	6 855	0	10	16 100	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	14 748	13 997
1998–99	3 845	3 632	3 324	3 500	8 165	6 855	0	10	15 334	13 997
1999–00	3 899	3 632	2 803	3 500	6 898	6 855	0	10	13 600	13 997
2000–01	3 429	3 632	2 321	3 500	8 360	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	11 580	14 066
2003–04	3 466	3 701	2 275	3 500	7 945	6 855	0	10	13 686	14 066
2004–05	4 795	3 701	1 264	1 800	7 317	6 855	0	10	13 376	12 366
2005–06	2 743	3 701	305	1 800	6 906	7 700	0	10	9 954	13 211
2006–07	2 025	3 701	900	1 800	7 668	7 700	0	10	10 593	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	10 225	13 211
2009–10	2 156	3 701	208	1 800	2 352	7 700	0	10	4 716	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
2013–14	1 883	3 701	168	1 800	3 642	7 700	0	10	5 693	13 211
2014–15	1 725	3 701	304	1 800	6 219	7 700	0	10	8 248	13 211
2015–16	1 584	3 701	274	1 800	2 864	7 700	0	10	4 722	13 211
2016–17	1 175	3 701	268	1 800	4 701	7 700	0	10	6 144	13 211
2017–18	1 350	3 701	267	1 800	3 086	5 064	0	10	4 703	10 575
2018–19	896	3 701	183	1 800	1 563	5 064	0	10	2 642	10 575
2019–20	1 062	3 701	137	1 800	2 063	2 272	0	10	3 262	7 783
2020–21	1 503	3 701	207	1 800	1 368	2 272	0	10	3 077	7 783
2021–22	1 692	3 701	137	1 800	1 325	2 272	0	10	3 154	7 783

[1] FSU data.

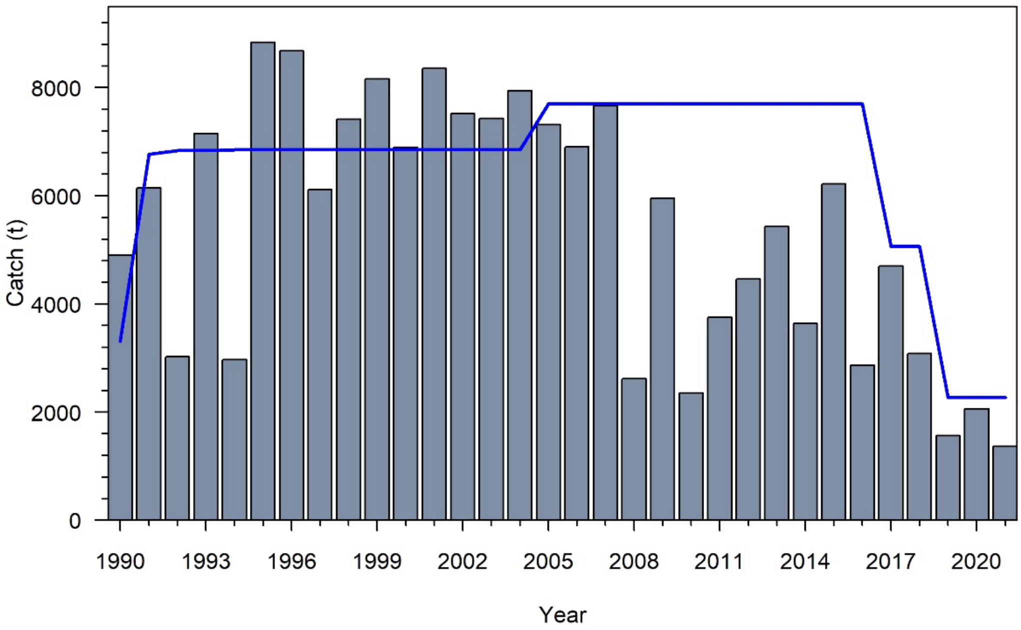

Figure 2: Annual reported catch of hake in HAK 7 (bars) and the TACC for hake (blue line) for the analysis fishing years 1989–90 (labelled 1990) to 2020–21 (labelled 2021).

Table 2: Total (scaled) catches (t) by stock for hake from 1990 to 2021 for (left columns) the October–September definition of a fishing year (where 1990 is 1 October 1989–30 September 1990), accounting for misreporting.

Fishing year	WCSI	Sub-Antarctic	Chatham Rise	Fishing year	WCSI	Sub-Antarctic	Chatham Rise
1974–75	71	120	191	1998–99	8 742	2 789	3 589
1975–76	5 005	281	488	1999–00	7 031	3 011	3 174
1976–77	17 806	372	1 288	2000–01	8 346	2 787	2 962
1977–78	498	762	34	2001–02	7 498	2 510	1 770
1978–79	4 737	364	609	2002–03	7 404	2 741	1 401
1979–80	3 600	350	750	2003–04	7 939	3 251	2 465
1980–81	2 565	272	997	2004–05	7 298	2 530	3 518
1981–82	1 625	179	596	2005–06	6 892	2 555	489
1982–83	745	448	302	2006–07	7 660	1 812	1 081
1983–84	945	722	344	2007–08	2 583	2 204	1 096
1984–85	965	525	544	2008–09	5 912	2 427	1 825
1985–86	1 918	818	362	2009–10	2 282	1 958	391
1986–87	3 755	713	509	2010–11	3 462	1 288	951
1987–88	3 009	1 095	574	2011–12	4 299	1 893	194
1988–89	8 696	1 827	804	2012–13	5 171	1 883	344
1989–90[1]	8 741	2 366	950	2013–14	3 387	1 832	187
1990–91[1]	8 246	2 749	931	2014–15	5 966	1 639	348
1991–92	3 010	3 265	2 418	2015–16	2 733	1 504	355
1992–93	7 059	1 452	2 798	2016–17	4 701	1 037	406
1993–94	2 971	1 844	2 934	2017–18	3 085	1 205	412
1994–95	9 535	2 888	3 271	2018–19	1 562	636	443
1995–96	9 082	2 273	3 959	2019–20	2 063	930	318
1996–97	6 838	2 599	3 890	2020–21	1 367	1 355	355
1997–98	7 674	2 789	4 074				

[1] West Coast South Island revised estimates for 1989–90 and 1990–91 were from Colman & Vignaux (1992) who corrected for under-reporting in 1989–90 and 1990–91, and not Dunn (2003a) who ignored such under-reporting.

2. SUMMARY OF THE HAKE FISHERY OFF THE WEST COAST SOUTH ISLAND

2.1 Available data

Data available for west coast South Island hake include catch and effort data, observer data from observed trips, and research resource surveys. Research surveys were primarily from the RV *Tangaroa*, but also include early surveys from the *Shinkai Maru* and *Amaltal Explorer* and inshore west coast South Island surveys from the RV *Kaharoa*.

Commercial catch and effort data were analysed to summarise and characterise the hake fishery and revise the CPUE indices for the stock. Catch and effort and landings of hake have been misreported by area, with hake caught in HAK 7 misreported as catch either in HAK 1 or HAK 4, with the majority misreported to the Chatham Rise (HAK 4 and the part of HAK 1 on the western Chatham Rise) (Dunn 2003a). While misreporting between the Chatham Rise and the sub-Antarctic was low, significant misreporting occurred between the west coast South Island and the Chatham Rise in the late 1990s (Dunn 2003a).

Catch and effort data were extracted by Fisheries New Zealand for the period from October 1989 to September 2021 (REPLOG 14055) that included all available data at the date of the extract (8th December 2021). The data extract included all data from trips where hoki, hake, or ling (*Genypterus blacodes*) were reported as caught, processed, or landed, and all fishing recorded on trawl catch, effort and processing returns (TCEPRs); trawl catch and effort returns (TCERs); catch, effort and landing returns (CELRs); lining catch and effort returns (LCERs); lining trip catch and effort returns (LTCERs); netting catch, effort and landing returns (NCELRs); electronic reporting system returns for all methods (ERS); and any high seas reports.

Observer data for hake from the Fisheries New Zealand observer sampling programme were also extracted, and data included all observer trips that reported hoki, hake, or ling as of 8th December 2021 (REPLOG 14055). Biological and length frequency data from these trips were also extracted, along with any associated otolith age readings. Additional age data (Richard Saunders, NIWA, pers. comm) for the 2021 survey, and the 2020 and 2021 commercial fisheries were included in this analysis but were not available on the Fisheries New Zealand age database at the time of this analysis.

Resource survey data (including data from the *Tangaroa* offshore west coast South Island standardised trawl survey and any other research voyages that reported hake) were extracted by Fisheries New Zealand from its research database, along with any biological and length frequency information and associated otolith age readings from these trips. A summary of the biomass estimates from the resource surveys for hake on the Chatham Rise, Sub-Antarctic, and west coast South Island are given in Appendix A.

2.2 Methods

Catch and effort data were checked for errors, using simple checking and imputation algorithms similar to those reported by Dunn et al. (2021b) and implemented in the software package R (R Core Team 2021). Individual tows were investigated, and errors were corrected using median imputation for start/finish latitude or longitude, fishing method, target species, tow speed, net depth, bottom depth, wingspread, duration, and headline height for each fishing day for each vessel. Range checks were defined for the remaining attributes to identify potential outliers in the data. The outliers were checked and corrected with median or mean imputation on larger ranges of data such as vessel, target species, and fishing method for a year or month. Transposition of some data was carried out (e.g., bottom depth and depth of net) to correct potential recording errors. The tow-by-tow commercial and observed catches of hake were corrected for possible misreporting between 1990 and 2007 according to the methods of Dunn (2003a).

Fish biological stocks (and statistical areas) were assigned based on the corrected positions or the reported statistical area where no location was available. Vessels were assigned as having a meal plant or not based on vessel name provided by Fisheries New Zealand on 2nd February 2021, noting that no date range was available for this information. Tows carried out with midwater gear (MW) but with fishing depth within five metres of the bottom were recoded as midwater bottom gear (MB).

2.3 Results

The TACC for hake has been stable in the HAK 1 and HAK 4 QMAs since 2004–05. In HAK 7, the TACC was reduced from 7700 t to 5064 t in 2016–17, and then again to 2272 t in 2019–20. Most hake are caught in HAK 7, off the west coast South Island, with a decreasing proportion caught in HAK 4. Over all areas, catches of hake have significantly declined since the mid-2000s as the commercial value of hake has declined. Catches of hake peaked in 1995–96 at about 16 000 t from a total TACC of 13 997 t. But, by 2020–21, the catch of hake across all areas has significantly reduced and is now 3077 t, less than half of the available TACC of 7783 t.

Off the west coast South Island, hake catches have declined from a peak of about 8600 t in 1995 to about 7300 t in 2007, and then dropping to less than 2000 t in recent years. Almost all catches were reported using TCEPR forms up to 2016–17, with subsequent data collection then switching to the ERS (Figure 3).

Hake have been caught predominantly by bottom trawls or midwater gear fished at or near the sea floor (Figure 4) from trawls targeting hoki, hake, or ling. Hake caught from hoki target tows made up a significant proportion of the catch up to 2003–04, but hake target tows became the predominate source of catch following the reduction in hoki availability and the hoki TACC in 2005–06 (McGregor et al. 2022). Over the past 4 years, the proportion of hake from hoki tows has increased, likely due to a few vessels that specialised in hake off the west coast of the South Island leaving the fishery (Figure 5).

Hake are caught mostly during the winter months off the west coast South Island (Figure 6) from a trawl fleet dominated by vessels 60 to 70 m in length. The trawl fleet is mostly New Zealand or formerly Japanese flagged vessels, with a few vessels that were previously flagged to Korea. Vessels recorded as ‘other’ in the years 1990–1995 were previously identified as likely to be flagged to Japan and Norway by Ballara (2018). The location of catches has remained relatively stable over time, with most of the variation occurring with the change from hoki target catch to hake target catch from about 2004–05. Although the trawl fleet targeting hoki and other species has also fished in Statistical Areas 033, 034, 036, and 703, most of the hake catch was taken from Statistical Area 034 (Figure 7) at depths of 500 to 750 m.

To represent the expansion or retraction of the area fished, the area covered by the fleet was investigated using a 0.1° cell grid, by summarising the number of cells fished in any one year as well as the cumulative number of new cells fished over time. The bottom trawl fleet showed an increase in the new areas explored to about 2004–05, followed by a subsequent plateau (very few new areas investigated) with an annual expansion or contraction of the area fished in any one year (Figure 8). The change in the pattern of cells fished occurred at the time of the change in target species and the reduction in the number of statistical areas fished. There was an increase from 2014–15 in the number of 0.1° cells fished, due to a small amount of range expansion off the west coast South Island and as a consequence of the change in reporting systems from TCEPR forms to the higher resolution position data reported on ERS-trawl data forms.

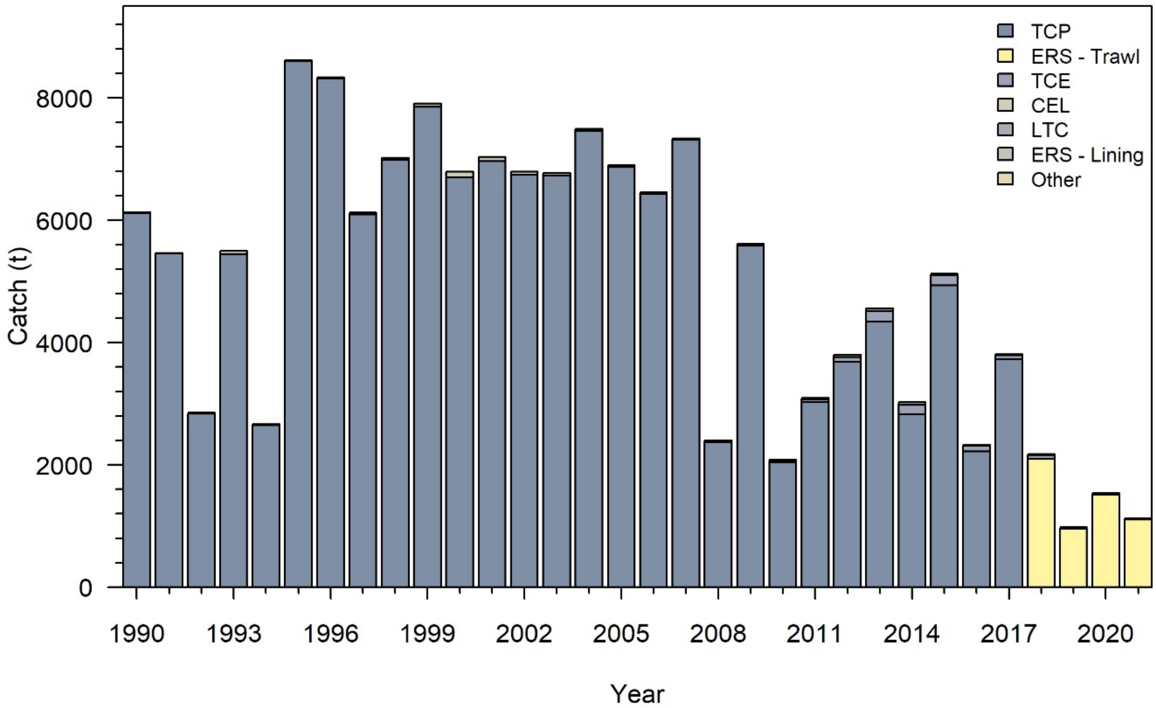

Figure 3: Total catch of hake (t) for the west coast South Island by data reporting form type and fishing year from 1989–90 to 2020–21.

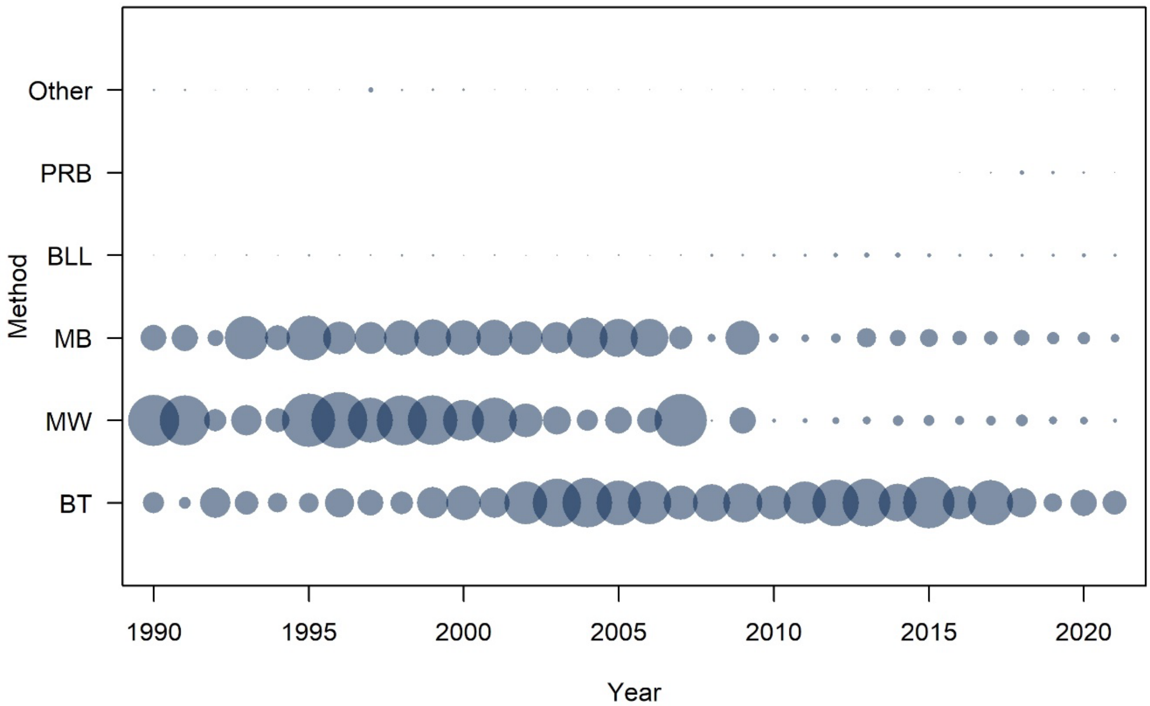

Figure 4: Relative proportion of hake catch for the west coast South Island by gear type (BT = bottom trawl gear, MW = midwater trawl gear, MB = midwater trawl gear fished near the sea floor, BLL = bottom longline, PRB = modular harvesting system bottom trawl gear, and Other = all other gears combined) and fishing year, from 1989–90 to 2020–21.

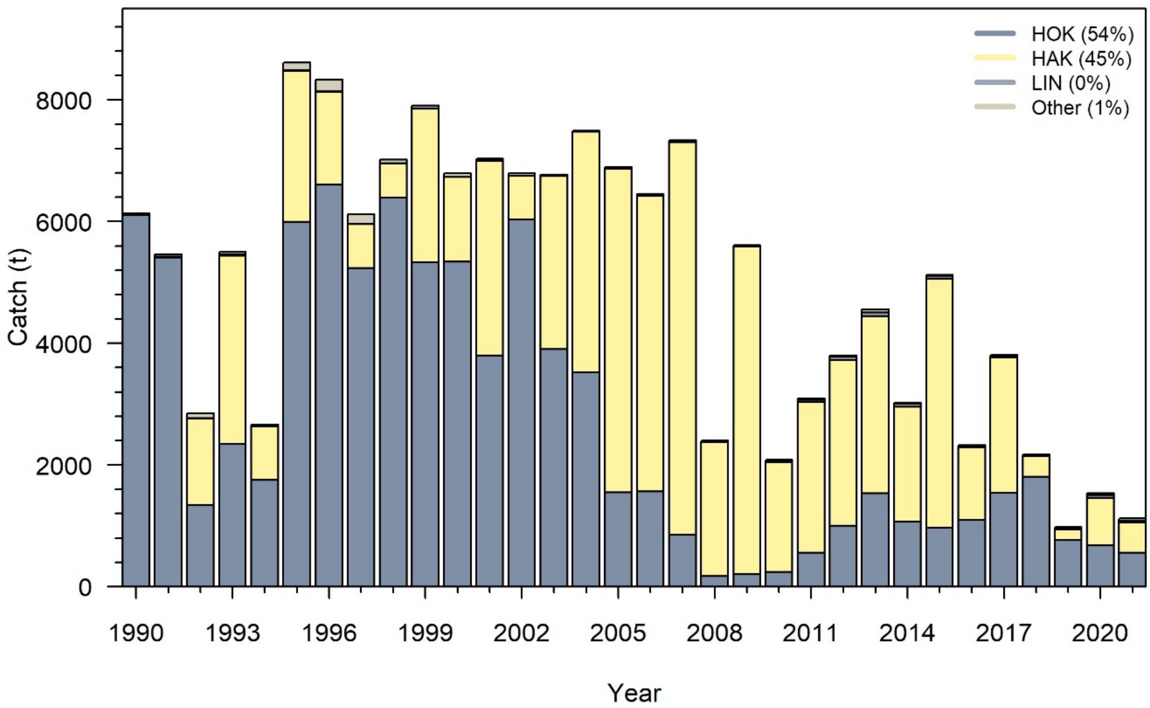

Figure 5: Total catch (t) of hake for the west coast South Island by target species (hake, hoki, ling, and other species combined) by fishing year, from 1989–90 to 2020–21, and proportion of the catch for all years combined.

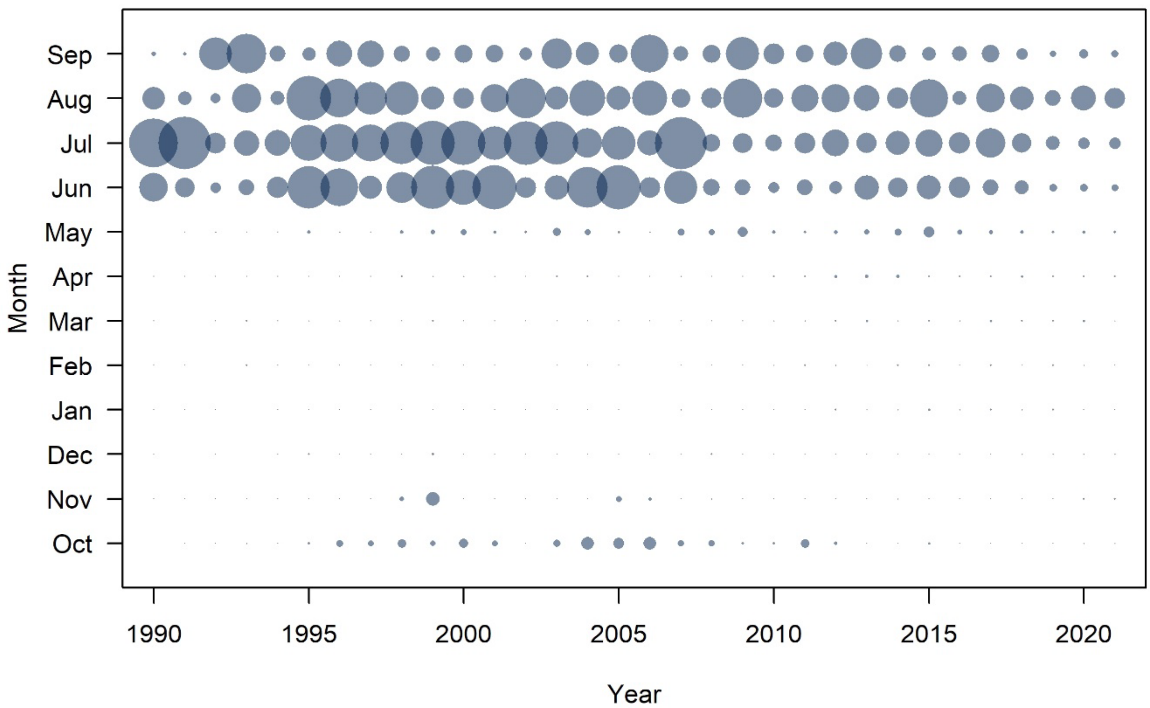

Figure 6: Relative catch of hake for the west coast South Island by month and fishing year from 1989–90 to 2020–21.

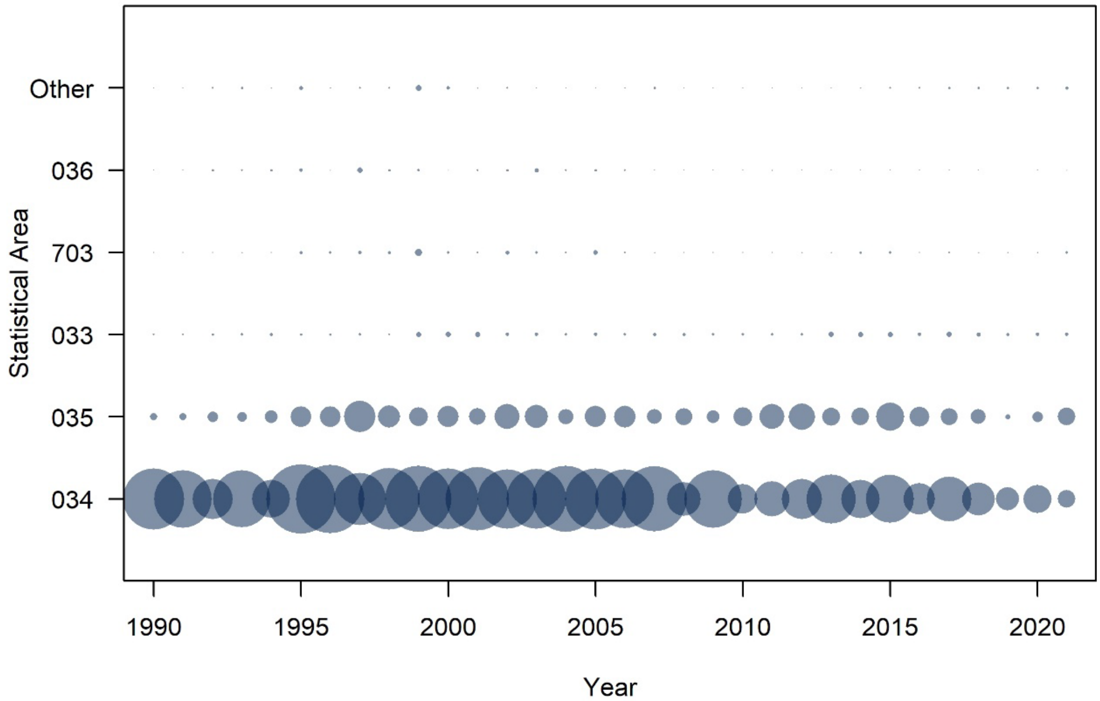

Figure 7: Relative catch of hake for the west coast South Island, by statistical area and fishing year from 1989–90 to 2020–21. Other represents Statistical Areas 701, 702, and 704–706.

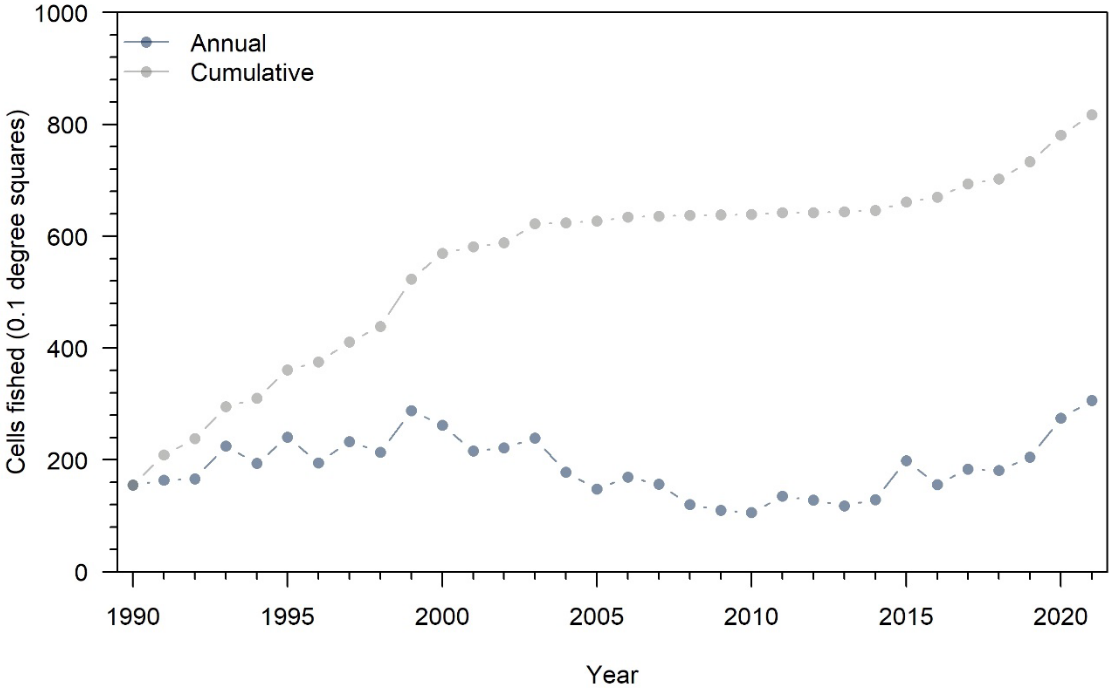

Figure 8: Annual and cumulative number of 0.1° cells for the west coast South Island that had reported hake catch, by fishing year, from 1989–90 to 2020–21.

3. SPATIAL-TEMPORAL ANALYSES

Spatial-temporal analyses of the hake catch data from off the west coast South Island were undertaken to investigate if there were suitable sub-fleet, spatial, or temporal splits that would allow the development of consistent fishing selectivity patterns or suitable subsets of data for CPUE analyses. For example, if hake were distributed differently by age or sex over spatial areas (depth or location) then the changing pattern of the fishery would introduce changes in selectivity or in CPUE indices over time that an assessment model may interpret as a population dynamic, rather than a spatial-temporal dynamic of the fishery.

The spatial strata used in previous analyses for west coast South Island hake were derived from a 2005 analysis by Horn (2011) and have been used since to scale length frequencies to produce a single area combined age frequency (Saunders et al. 2021), to estimate the selectivity for the single fishery within the west coast South Island hake stock assessment (Kienzle et al. 2019), and as a potential explanatory factor in the hake CPUE analyses (Finucci 2019). Horn (2011) determined that there were three strata for the hake fisheries off the west coast South Island: ‘south shallow’, south of 42.55° S and shallower than 629 m depth; ‘north shallow’, north of 42.55° S and shallower than 629 m depth; and ‘deep’, all other areas deeper than 629 m.

Describing and modelling the spatial distribution of mean length or age and correcting for variables such as month and year (i.e., analogous to that used for CPUE standardisations) can help better understand the spatial and temporal patterns in fish size and age. Looking at the data alone can result in biased conclusions as the spatial-temporal patterns of fish size/age may be different depending on when and where fishing occurred.

3.1 Methods

3.1.1 Tree regression

A series of tree regression analyses were carried out following a similar procedure to that used to establish the fisheries in the toothfish Ross Sea Region stock assessment (Mormede & Parker 2018). The analysis was implemented in the software package R (R Core Team 2021) using the R package *rpart*. A tree regression using the mean length of hake per fishing event was carried out for bottom trawl catch; potential parameters offered to the regression are detailed in Table 3. A similar tree regression analysis was carried out for the sex ratio (expressed as the proportion of females) in each fishing event.

Tree regression was also carried out using the same methods but applied to the age data instead of the length data. Although the amount of age data was significantly lower than that for length, it was more likely to be able to resolve any patterns in the distribution of older fish than the length frequency analysis; however, this approach could introduce a bias due to the non-random selection of fish that were sampled by observers and then aged.

Table 3: Explanatory variables offered to the tree regression model.

Variable	Type	Description
Month	Categorical	Month of the year
Week of year	Numeric	Week of the year, starting on 1 September
Day of year	Numeric	Julian date, starting at 1 on 1 September
Statistical area	Categorical	Statistical area
Start latitude	Numeric	Start latitude (absolute value)
Start longitude	Numeric	Start longitude (0–360)
Target	Categorical	Species targeted on the tow
Bottom depth	Numeric	Depth of the bottom in metres
Fishing duration	Numeric	Duration of the tow in hours

3.1.2 Bayesian spatial-temporal analysis

A spatial mesh (i.e., made up of nodes connected by edges to delineate spatial regions) was developed using constrained Delaunay triangulation (Figure 9). The mesh was limited to 1500 nodes (i.e., the number of nodes was constrained to be at least about 10 times less than the number of observations, while still maintaining an appropriate spatial resolution). Following an initial analysis using all available data, the data were partitioned into sub-adult (immediately pre-mature) and adult (mature) fish by excluding juvenile fish (i.e., fish of size that were likely to be immature, less than 65 cm for males and 69 cm for females). The analysis using all available length measurements suggested significant confounding by a small number of juvenile fish that occurred across the west coast South Island (Figure 10) inconsistent with the size-based structure found in larger fish. Hence, analyses ignored the juvenile fish and focused on the larger sub-adult and adult fish.

Each node was an estimated model parameter, constrained by the stochastic partial differential equation (SPDE) underpinning integrated nested Laplace approximation (INLA) spatial smoothers.

Two different data sets were used in this analysis: length frequency (LF) data (n = 321 844) and age frequency (age) data (n = 14 429). LF data were combined with the lengths available in the age data set (length is also recorded in the age data set); records with unknown sex were dropped; length was rounded down to the nearest integer. In addition, records with unknown sex were also dropped from the age data and ages were rounded to the nearest integer.

The length data were fitted assuming a normal distribution—the minimum length recorded was well away from zero—because models specified using the normal distribution can be run in reasonable time when using INLA. The age data were fitted assuming a Poisson distribution. The variables year, month, sex, and spatial structure (i.e., node) were offered to models for both data sets. Spatial structure was assumed to be either constant, sex-specific, or year specific, depending on the model run. Although there may be correlations within tows in the length and age data, any such correlations were ignored in these analyses, and it was assumed that each length was an independent sample from the population at that time in that location for each sex. Further development of this method could investigate the inclusion of the tow as a random-effect term within the model because this may better account for the variability and correlation of individual lengths within tows. Any correlations between ages from the same tow were less likely to have a similar concern as only a few otoliths are sampled within each tow with a subset of these being aged. Both the deviance information criterion (DIC) and Watanabe-Akaike information criterion (WAIC) were used for model comparison.

Finally, the R package *ClustGeo* was used to derive spatial fishery strata using hierarchical clustering with geographic constraints (Chavent et al. 2018). The *ClustGeo* package implements a clustering algorithm that includes soft contiguity constraints. The algorithm requires two dissimilarity matrices (D0 and D1) and a mixing parameter alpha. D0 is a matrix containing the Euclidean distance between all data points, and D1 is a matrix containing the distance in space (in metres) between all data points. The alpha parameter (a real value between 0 and 1) stipulates the relative importance of the data (D0) compared with space (D1).

The value of alpha can be somewhat subjective and can radically change the clusters. However, a somewhat objective method for finding a good starting value for alpha involves:

1. defining the number of clusters (e.g., K = 3 clusters),
2. running the clustering algorithm for evenly spaced values of alpha between 0 and 1 (e.g., alpha = {0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0}), and
3. examining a plot of the proportion of explained inertia of the partitions in K clusters for each alpha value and deciding on an alpha value.

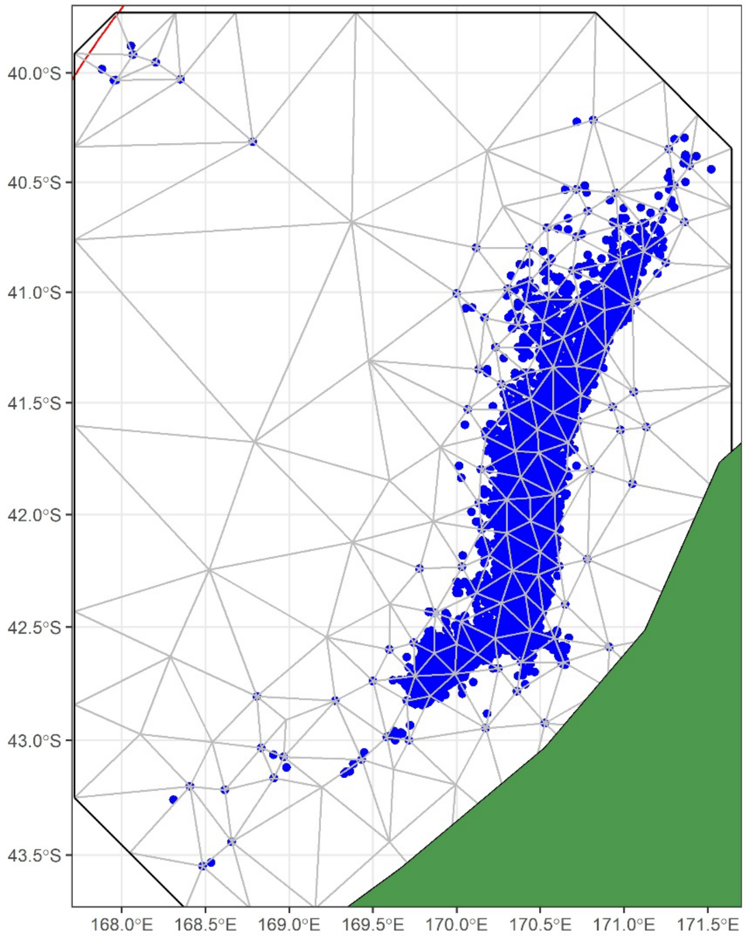

Figure 9: Spatial mesh for the west coast South Island hake spatial-temporal models showing the locations of data (blue points), the spatial mesh (grey lines), the extent of the spatial model (thick black lines), and the New Zealand EEZ (red line).

3.2 Results

An initial investigation of the length structure across the biological stocks was carried out. Unscaled length frequencies were plotted for all hake measured in HAK 1, HAK 4, and HAK 7. Although the largest fish were found in the Sub-Antarctic, most of the range of lengths were observed in each of the three stock areas (west coast South Island, Chatham Rise, and the Sub-Antarctic) and there was no evidence from the length frequencies that contradicted the current stock structure assumptions (Figure 10).

Tree regression analyses for the west coast South Island suggested that the lengths could be clustered into three main spatial strata (with two additional much smaller and minor strata), but with no evidence of temporal splits (Figure 11). These spatial strata suggested the presence of sub-adult and adult fish in the main area fished off the west coast South Island, larger fish in and immediately south of the Hokitika Canyon, and the largest fish at the head of the Hokitika Canyon. The spatial stratification resulting from the tree regression did not significantly modify the spatial strata of Horn (2011).

Application of the Bayesian spatial-temporal analysis allowed the consideration of spatially non-contiguous areas, i.e., locations where the age and/or length structure was similar but was not located in a neighbouring location. Both the DIC and WAIC suggested the models that included terms of year, sex, and space were the most parsimonious. The spatial effect for the model of mean length with sex and space is shown in Figure 12 and Figure 13, and for mean age in Figure 14. The estimated mean age model with annually varying effects is shown in Figure 15.

Alpha levels of between 0.15 and 0.25 were considered optimal (Figure 16). Clustering was investigated for K = 3, 4, and 5 clusters and the relative catch between each cluster compared over the time series of hake lengths and ages. The application of three or four clusters grouped almost all of the relative catch into three areas similar to that for the tree regression and the analysis of Horn (2011). The relative catches were dominated by two clusters but suggested a pattern of similar proportions of catch from these two clusters up to 2004, then diverged with a small but increasing proportion of catch in cluster 3 (Figure 17). The pattern of change in the relative proportions of catch from the length and age frequency Bayesian spatial-temporal analyses closely approximated the timing of the change in the targeting of hoki versus hake and contraction of hake catch from the mid-2000s.

While these clusters could be used to determine spatial structure of the commercial catch for use in an assessment model, the resulting pattern of age frequencies was broadly similar to the age frequencies resulting from the strata defined by Horn (2011). Qualitative evaluation of the available age data and initial model runs suggested that ignoring the Bayesian stratification in determining spatially explicit strata for the age frequencies did not result in any modification to the west coast South Island stock assessment (see Dunn et al. 2023).

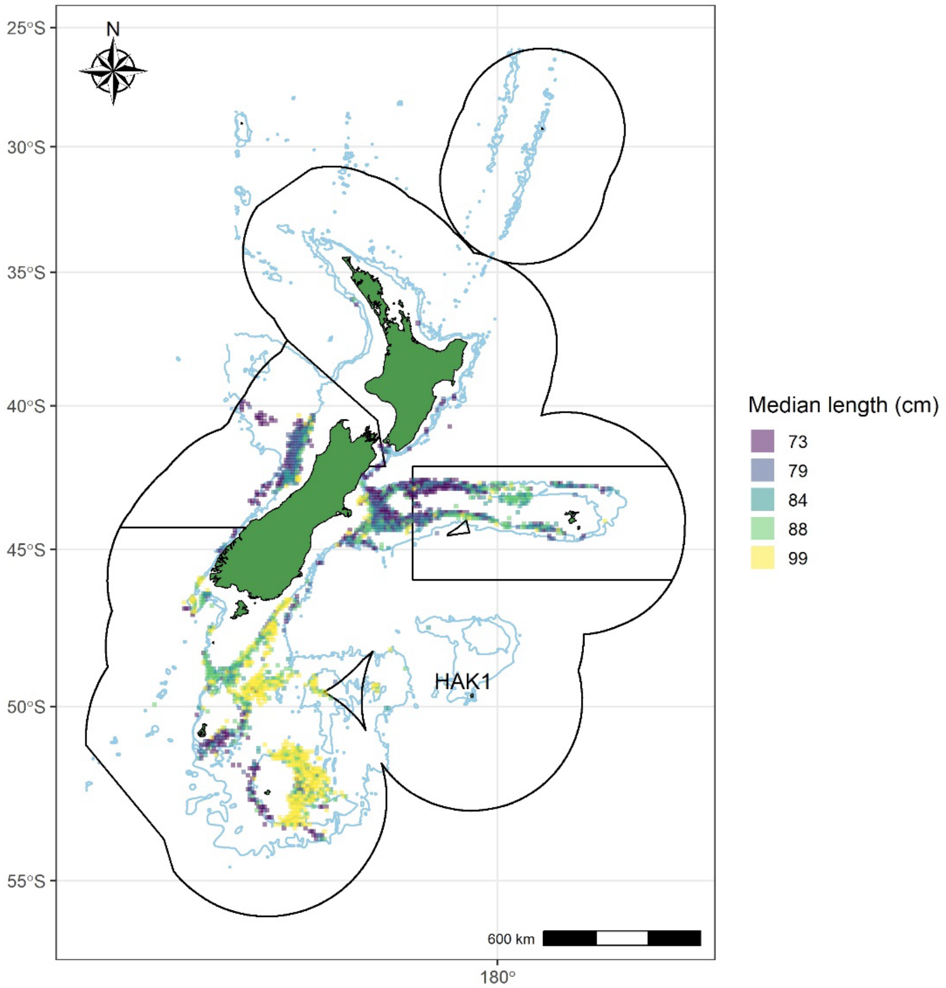

Figure 10: Observed median length of hake within the New Zealand EEZ by 0.1° cell with strata defined by the tree regression, for males and females combined for years 1989–90 to 2020–21. Also plotted are the hake QMAs and 500 m and 1000 m depth contours.

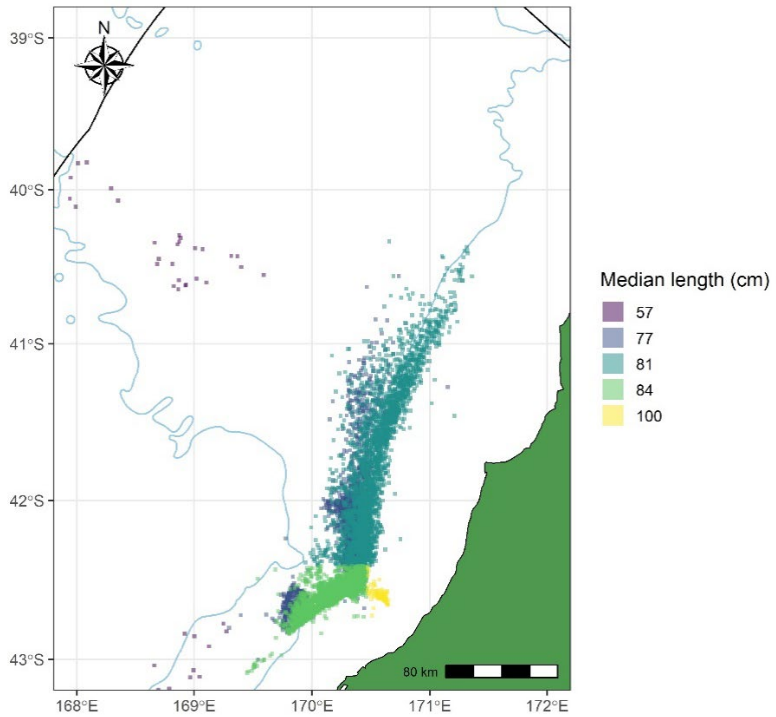

Figure 11: Estimated spatial strata using the tree regression on the median length of hake off the west coast South Island with strata defined by the tree regression, for males and females combined for years 1989–90 to 2020–21. Also plotted are the 500 m and 1000 m depth contours.

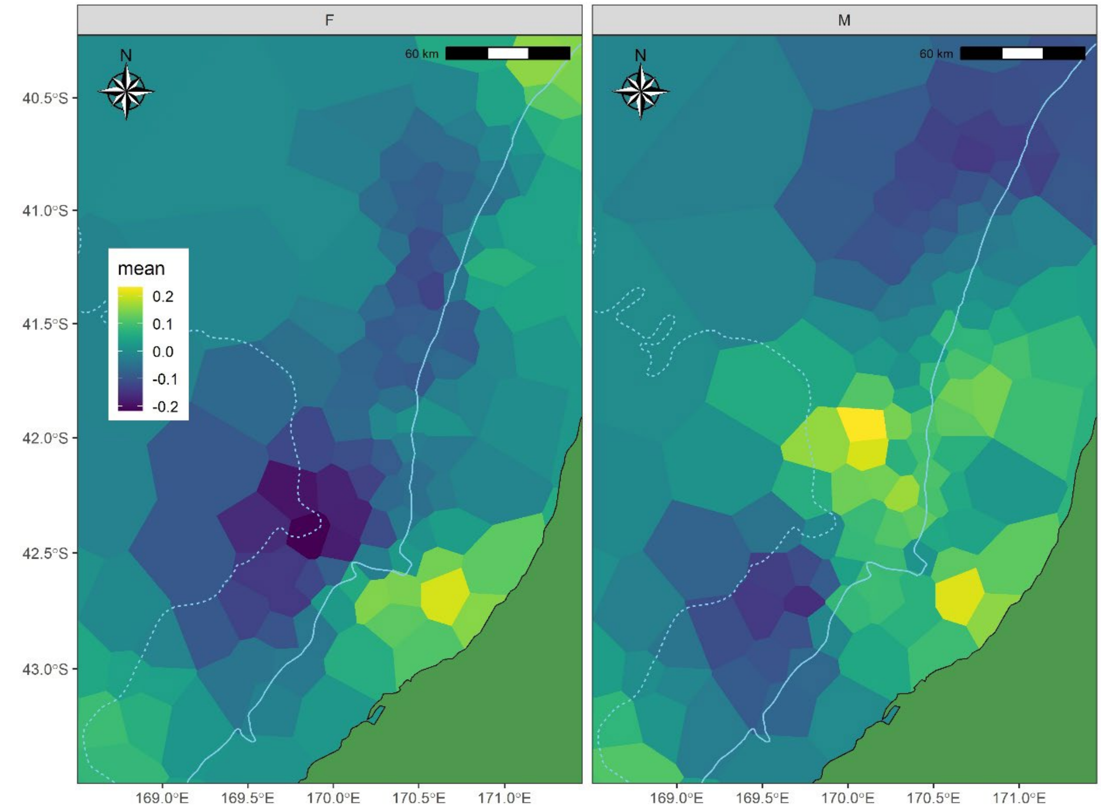

Figure 12: The sex and spatial effect for the model of mean length of sub-adult and adult fish (length ~ intercept + sex + space) and the resulting k=3-cluster spatial definition. Also plotted are the 500 m (white line) and 1000 m (broken white line) depth contours.

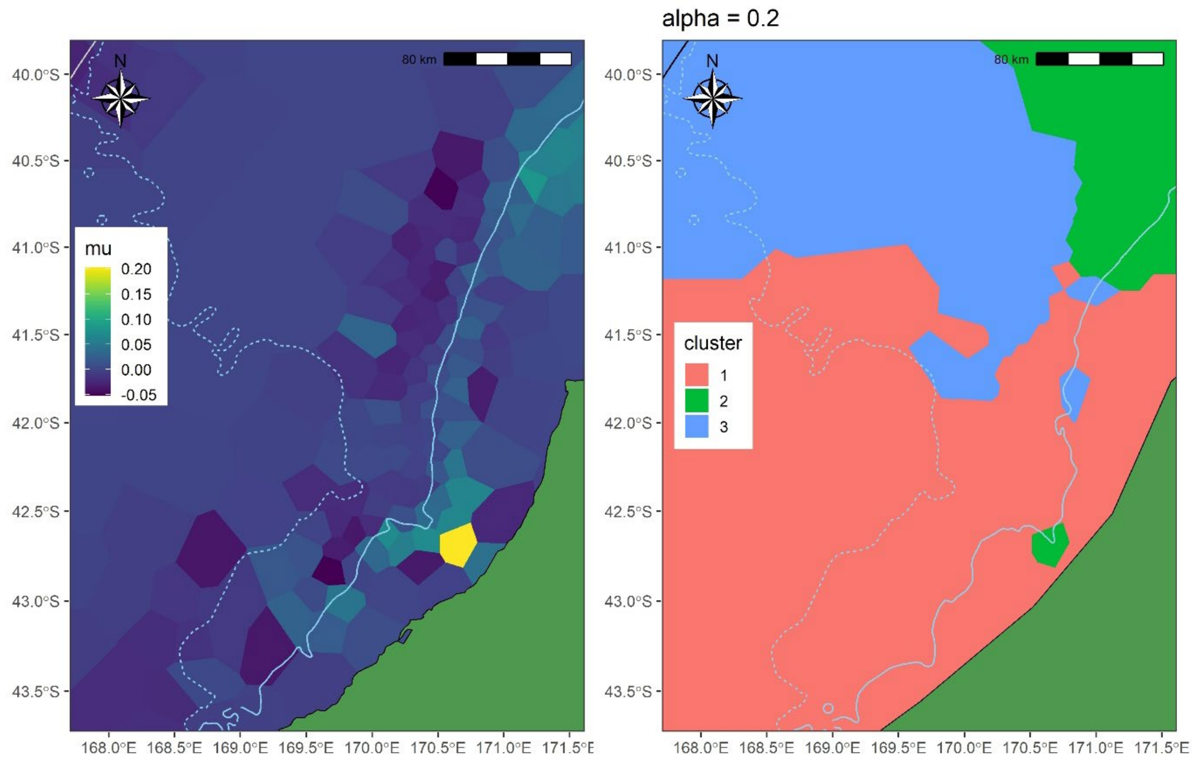

Figure 13: The spatial effect for the model of mean length of sub-adult and adult fish (length ~ intercept + sex + space) and the resulting k=3-cluster spatial definition. Also plotted are the 500 m (white line) and 1000 m (broken white line) depth contours.

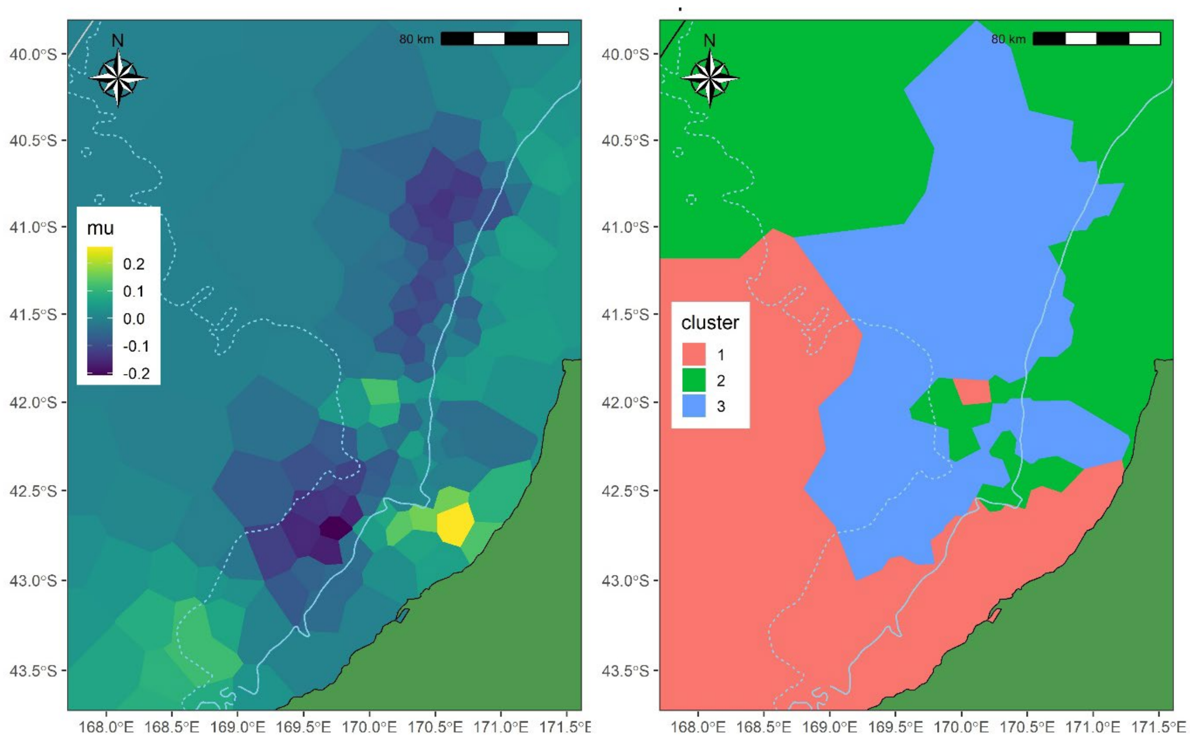

Figure 14: The spatial effect for the model of mean age of sub-adult and adult fish (length ~ intercept + sex + space) and the resulting k=3-cluster spatial definition. Also plotted are the 500 m (white line) and 1000 m (broken white line) depth contours.

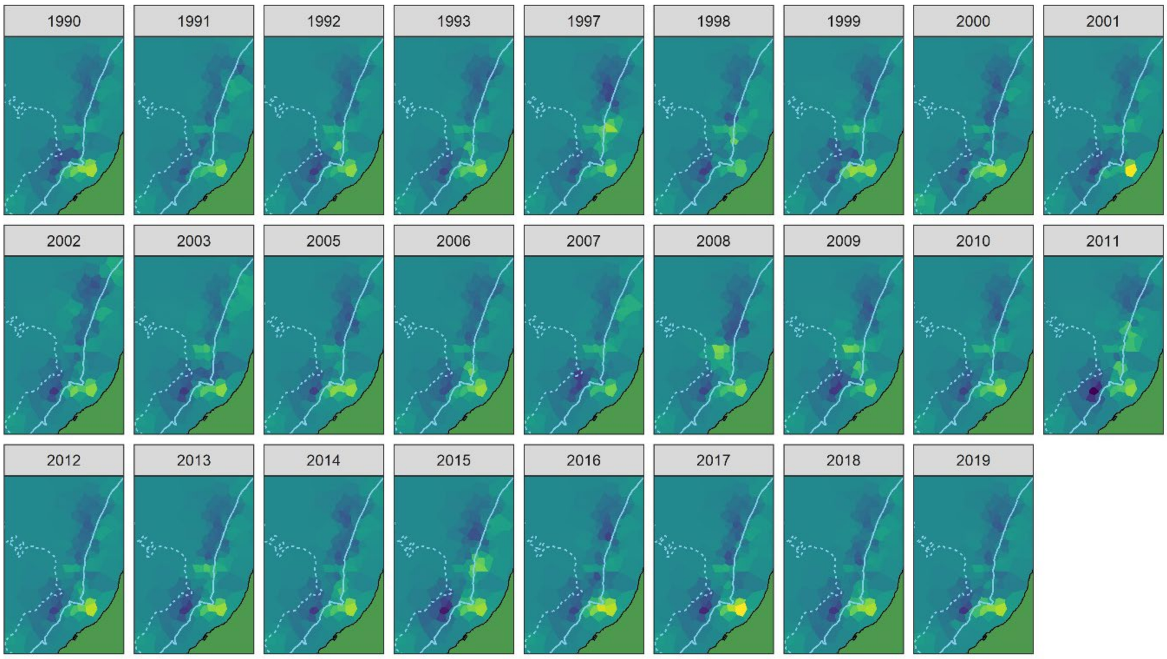

Figure 15: The spatial effect for the annually varying model of mean age (age ~ intercept + sex + (space × year)) for sub-adult and adult fish. Also plotted are the 500 m (white line) and 1000 m (broken white line) depth contours.

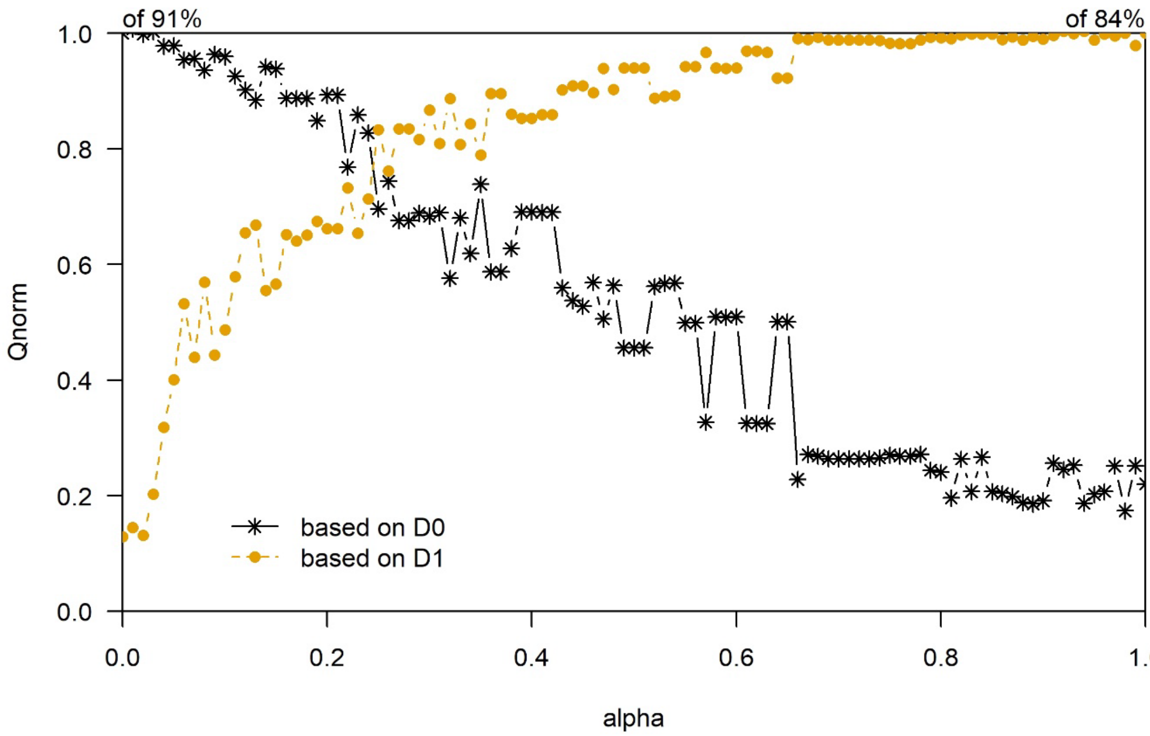

Figure 16: The proportion of explained inertia of the data (D0) and distance (D1) partitions (in K = 3 clusters) for different values of the mixing parameter alpha.

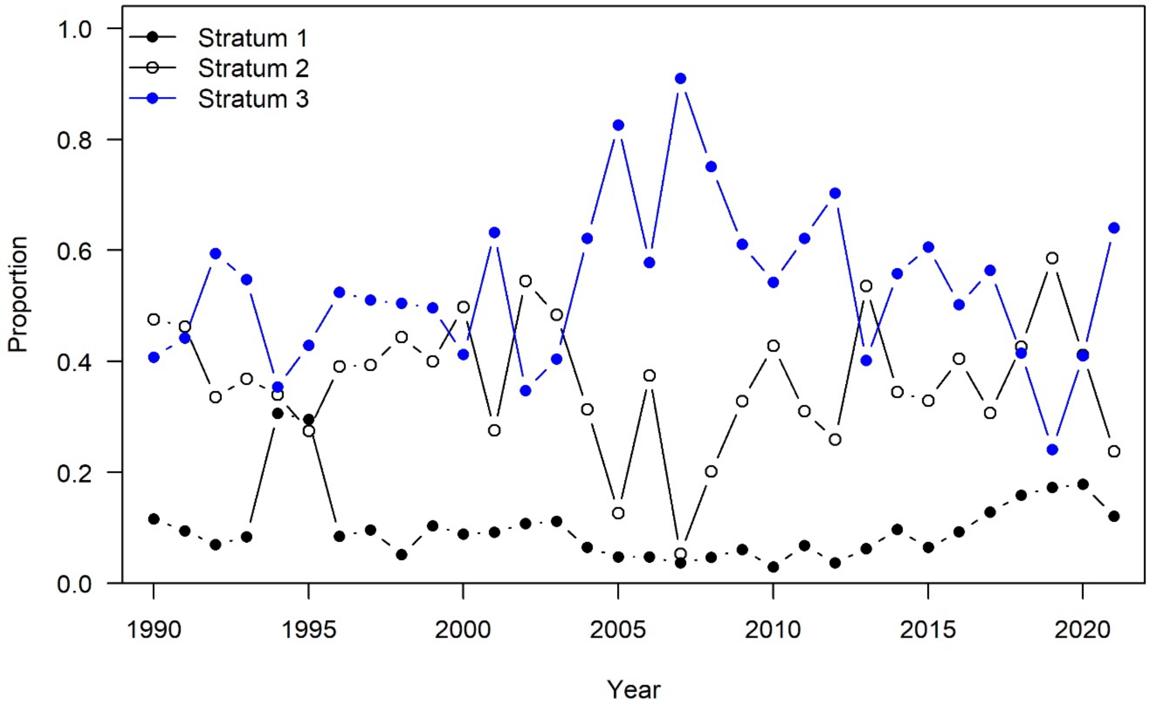

Figure 17: Relative catch of hake on the west coast South Island from allocation to the K = 3 clustering algorithm for the Bayesian spatial-temporal analysis of age by fishing year from 1989–90 to 2020–21.

4. BIOLOGICAL PARAMETERS

4.1 Length-weight parameters

Length-weight parameters for hake were last updated by Horn (2013a) based on data collected from resource surveys. Data from the resource surveys and other surveys from the west coast South Island were analysed to update the length-weight relationship ($n = 7001$). The numbers of length-weight observations by year for males and females is shown in Figure 18.

A log-linear regression was applied to the available length and weight parameters, where Weight = $a \cdot (\text{length})^b$, to estimate the a and b parameters for each sex separately (see Table 4 and Figure 19). Plots of residuals indicated reasonable fit to the data with the length-weight relationship, with no apparent pattern or trend over time (Figure 20). The resulting parameter estimates were only slightly different from those reported by Horn (2013a), and there was little discernible change in the shape of the resulting length-weight curves.

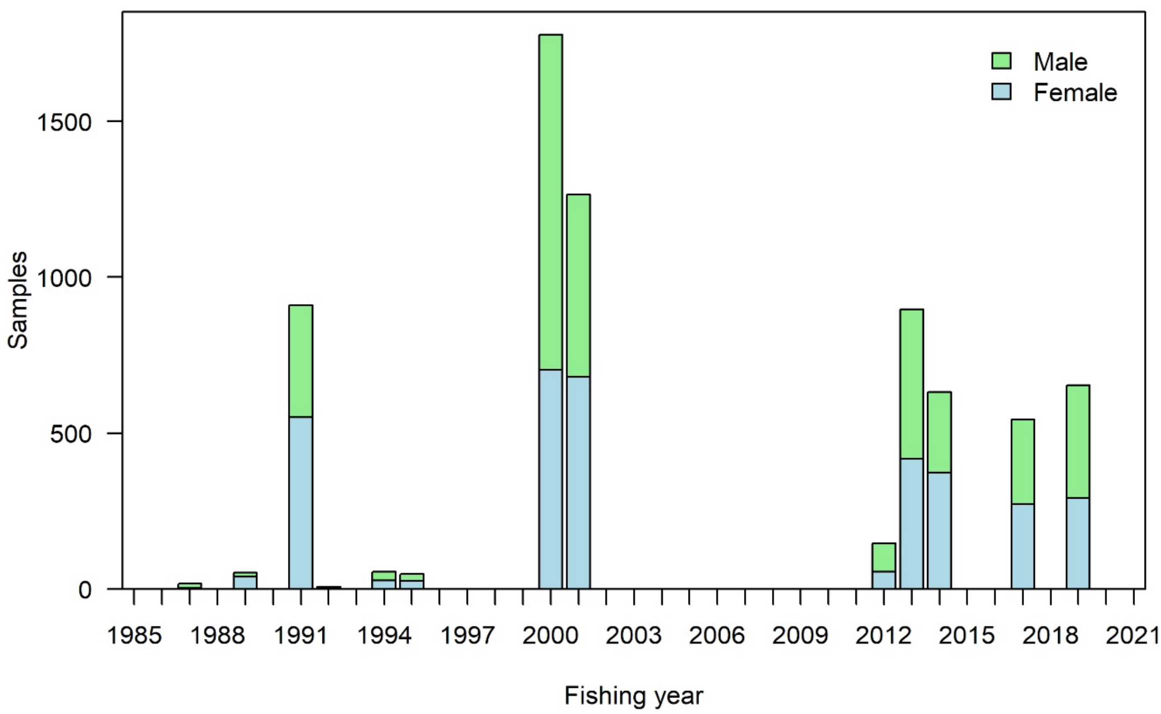

Figure 18: Number of length and weight observations for west coast South Island hake by sex and fishing year from 1988–89 to 2020–21.

Table 4: Estimated length-weight parameters from Horn (2013a) and from this analysis.

Sex	N	Parameter	Horn (2013a)	This analysis
Male	3 555	*a*	2.85e-06	3.34e-06
		b	3.209	3.175
Female	3 446	*a*	1.94e-06	3.48e-06
		b	3.307	3.177

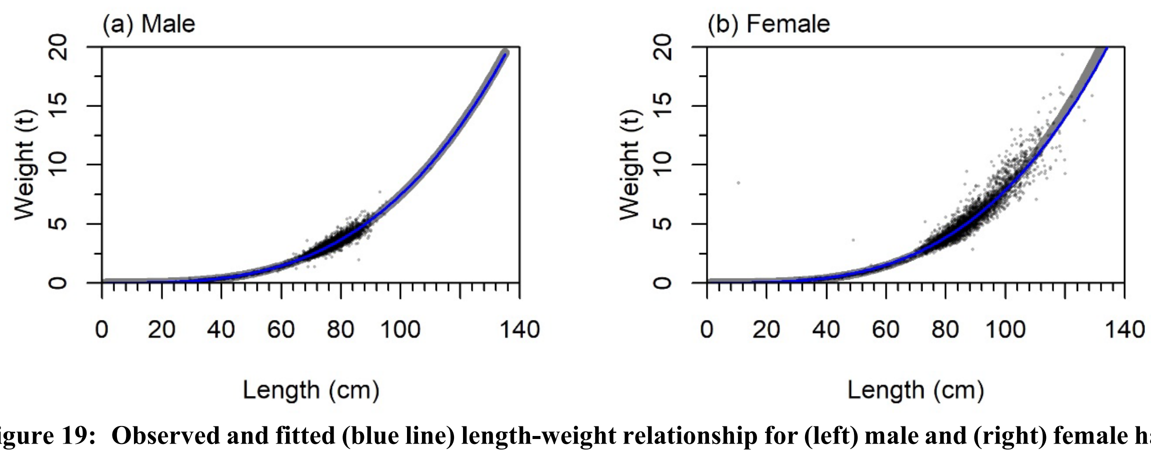

Figure 19: Observed and fitted (blue line) length-weight relationship for (left) male and (right) female hake for the west coast South Island. The relationship estimated by Horn (2013a) is given as a thick grey line.

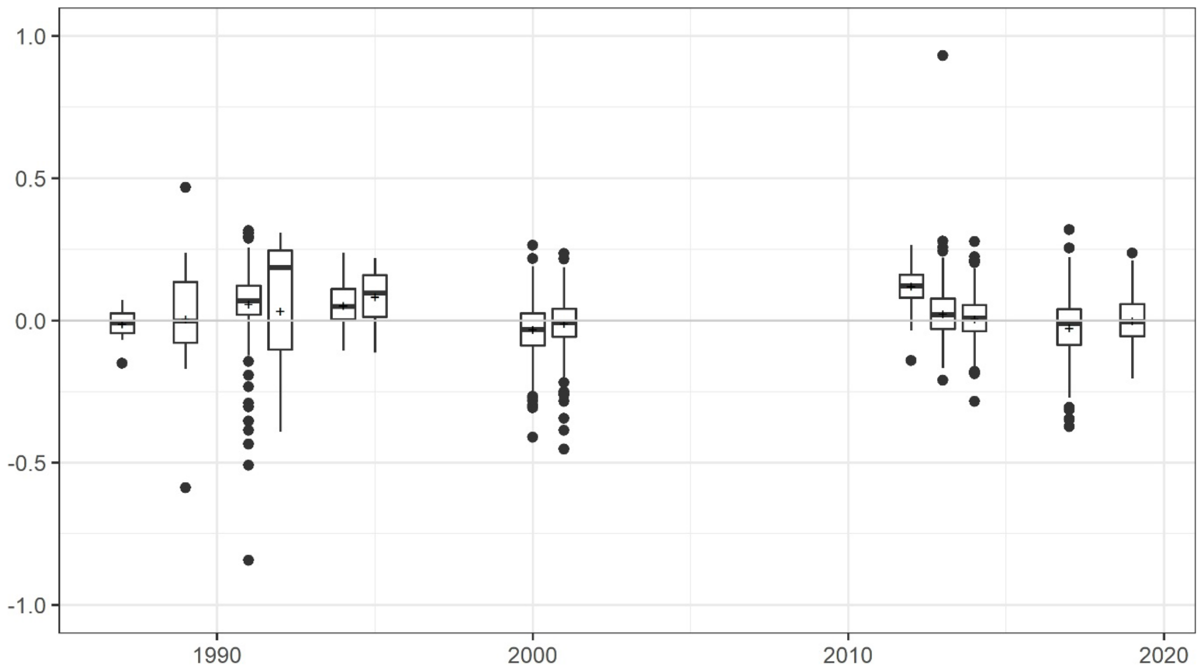

Figure 20: Boxplots of residuals (dark line = median; box = interquartile range; and values more than 1.5 times the interquartile range plotted as black circles) by fishing year (1986–87 to 2018–19), of the fitted length-weight relationship for west coast South Island hake, with the residuals for both sexes combined.

4.2 Age data

Commercial fishery age frequencies for the west coast South Island hake assessment are typically calculated as part of the Fisheries New Zealand middle-depths ageing project (see Saunders et al. 2021, Ballara et al. 2022); however, as the scaled age frequencies for this project investigated alternative age stratification and alternative age frequencies that separated out juvenile fish, the scaled age frequencies were empirically derived from scratch over the entire period of the available data for the fishery.

Initial investigation suggested that there were a low proportion of age-length observations recorded that were implausible for hake. The age data from the months of June to September were used as they represented a period of likely constant length-at-age and represented more than 99% of all age-length observations for the west coast South Island. The observations were groomed for outliers by removing hake of implausible length given their age (Figure 21). This removed less than 0.1% of the age-length data, and the resulting data were used to calculate the age-length keys for estimating the scaled age frequencies.

Scaled age frequencies were estimated by scaling observed sex and length frequencies in each tow to the catch from that tow, then aggregating over all tows and scaling to a stratum catch. Total aggregated length frequencies were calculated by summing over strata. Age frequencies were then estimated by applying an annual sex-specific age-length key.

The sub-adult sized fish (about 65 cm in length) are rarely observed in either the commercial length frequency data (Figure 22) or trawl surveys, with most fish being of a size consistent with estimates of the size at maturity. When sub-adult fish are observed, they have been seen in small numbers in orange roughy tows at the edge of the New Zealand EEZ on the western side of the Challenger Plateau. Analyses of the initial scaled age frequencies suggested that the proportion of juvenile fish in the population was possibly a random event in the catch, contributed a very small amount of biomass to the total catch, and hence may not be representative of the proportion of juvenile fish in the population. As a result, data for fish aged less than five were removed from the age-length key and scaled age frequencies were estimated for fish aged 5+ only. Estimated scaled age frequencies were then calculated for the three strata separately using a combined annual sex-specific age-length key using the aged fish from all strata.

Age observations for the years 1994, 1995, 1996, and 2004 were not recorded on Fisheries New Zealand databases. Records for the 2004 year was located (Richard Saunders, NIWA, pers. comm.), and the data subsequently entered on the age database. However, the loss of the 1994–1996 data makes the re-calculation and checking of the scaled age frequencies for those years not possible.

The resulting age frequencies for fish aged 5+ for the three strata are given in Figure 23, Figure 24, and Figure 25. Age frequency distributions for males and females for all strata combined are given in Figure 26.

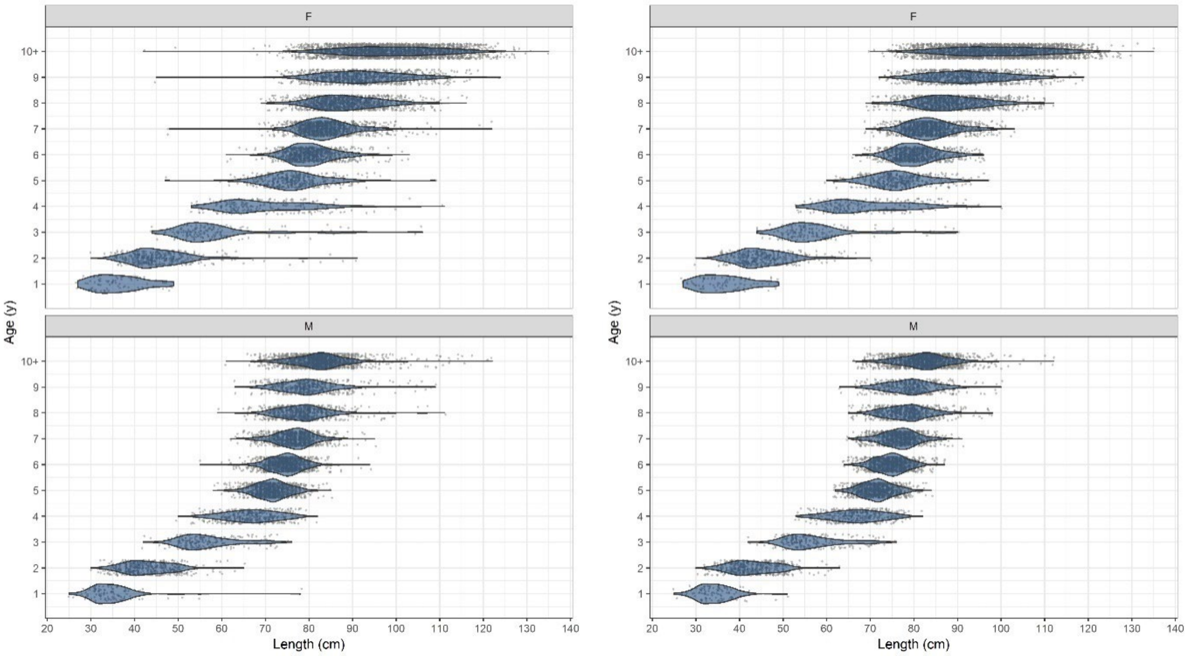

Figure 21: Distribution (violin plot) and observation (points) of the recorded length given age observations for male and female hake from off the west coast South Island (left plot) and the data after removing outliers (right plot).

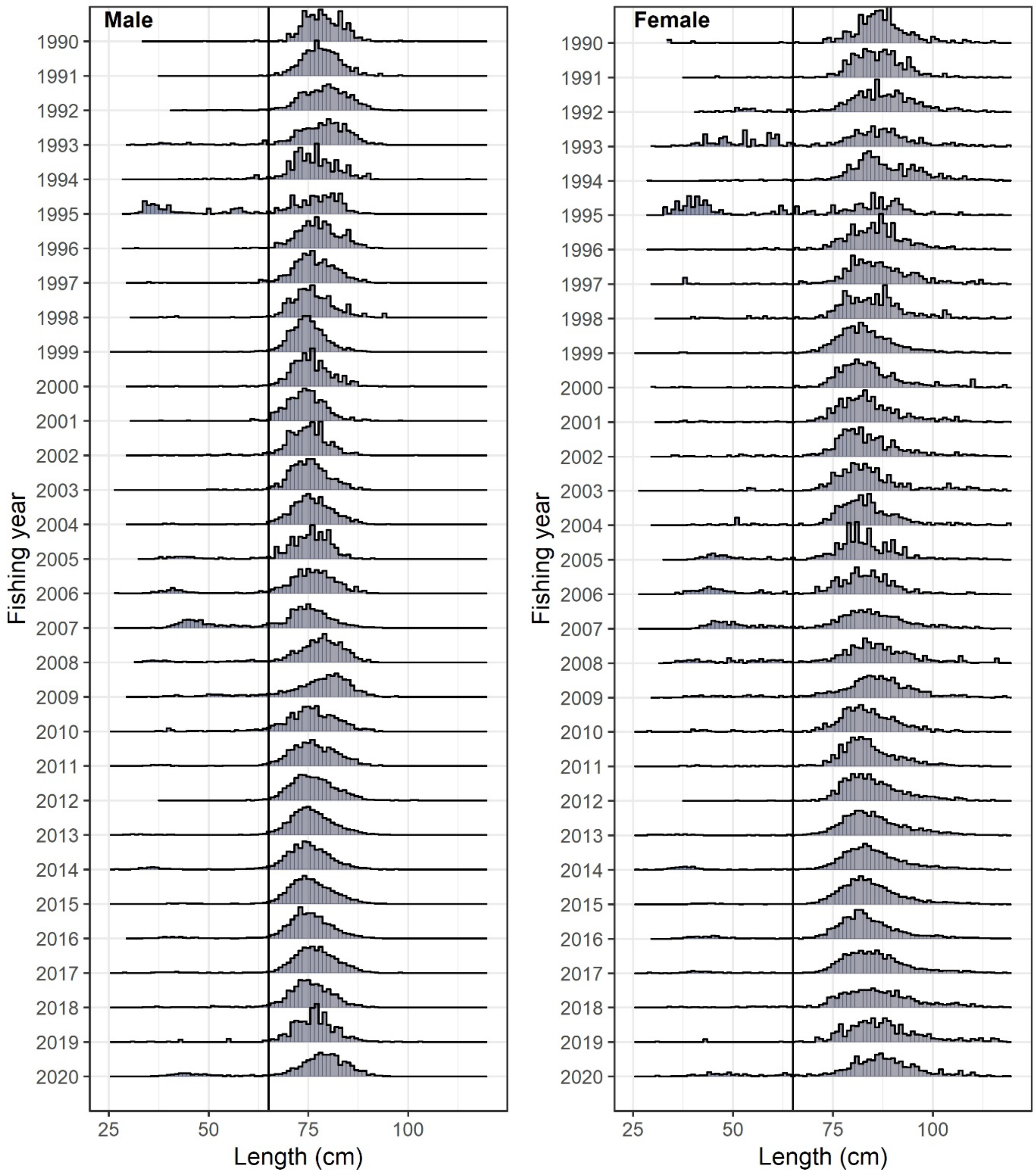

Figure 22: Observed scaled length frequency distributions for hake off the west coast South Island for 1989–90 to 2020–21. The solid vertical line indicates the cut-off for juvenile hake with lengths less than 65 cm for males and 69 cm for females.

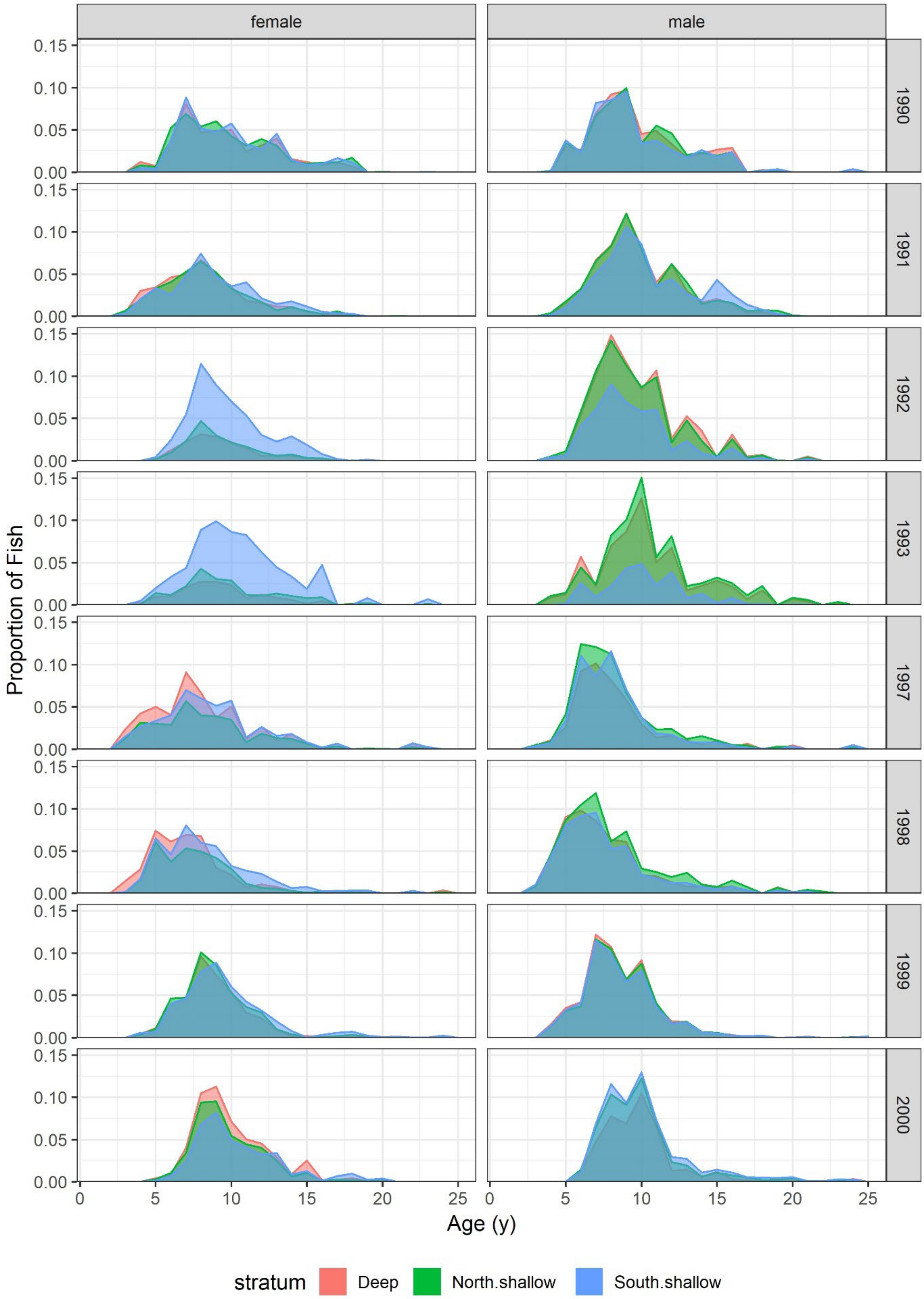

Figure 23: Estimated proportions-at-age distributions (for ages 5+) for the deep, north shallow, and south shallow strata for hake off the west coast South Island, 1990–2000.

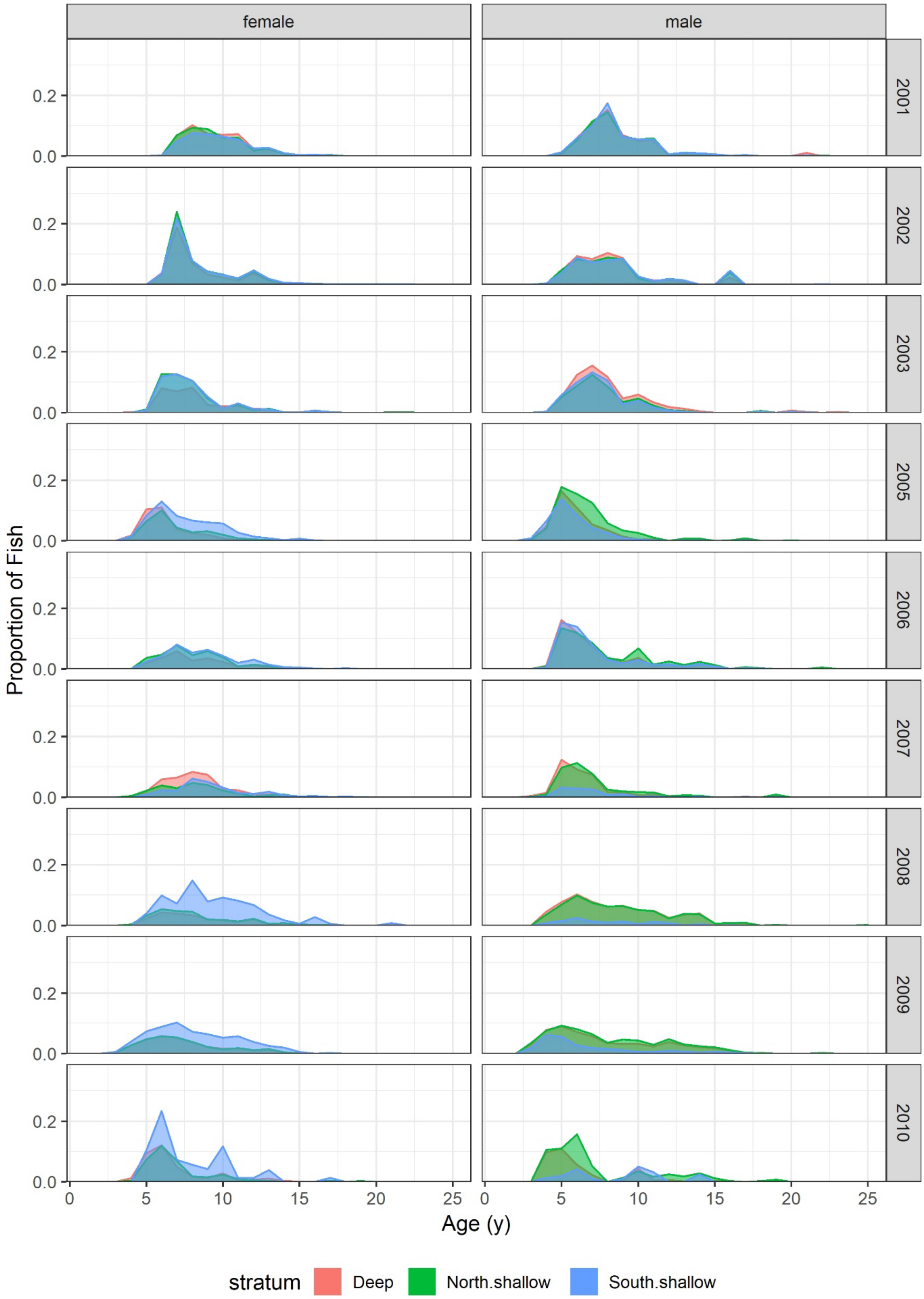

Figure 24: Estimated proportions-at-age distributions (for ages 5+) for the deep, north shallow, and south shallow strata for hake off the west coast South Island, 2001–2010.

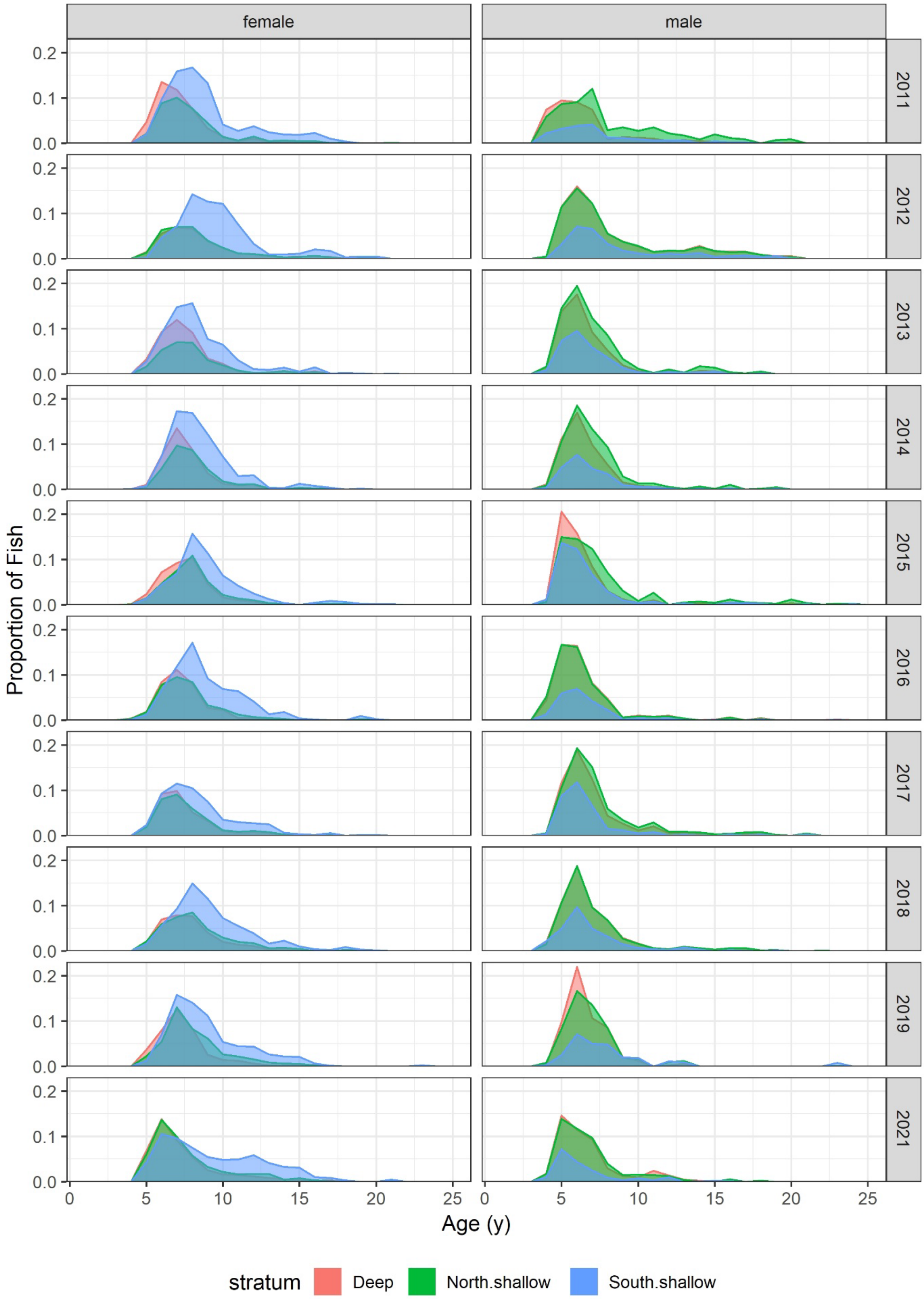

Figure 25: Estimated proportions-at-age distributions (for ages 5+) for the deep, north shallow, and south shallow strata for hake off the west coast South Island, 2011–2021.

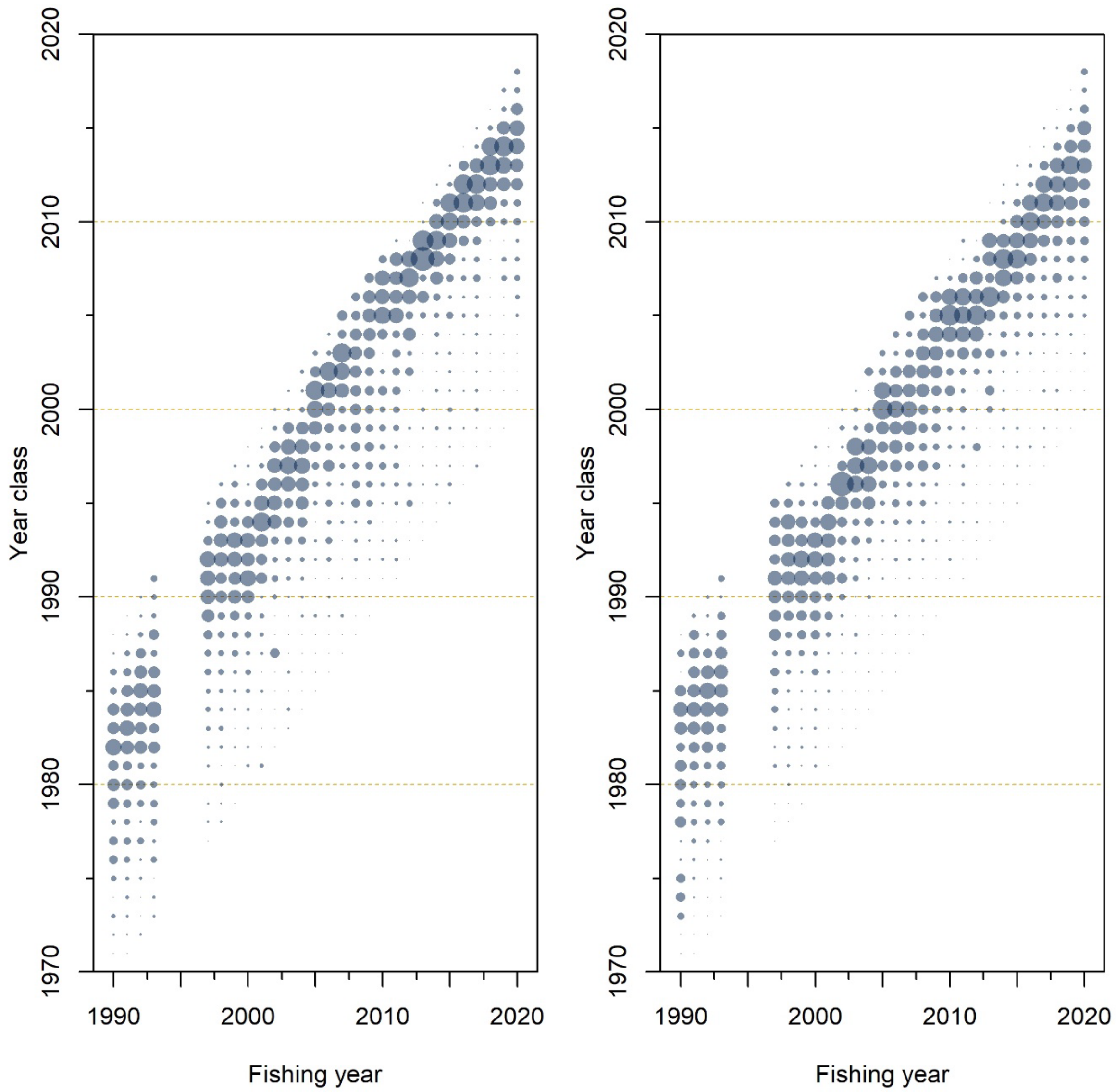

Figure 26: Estimated proportions-at-age by fishing year and sex for west coast South Island fishery (left) male and (right) female hake for the years from 1989–90 to 2019–20.

4.3 Growth models

Growth models were last updated by Horn (2008) (with a minor revision by Horn (2013a) who used the same data to estimate a combined-sex growth curve), parameterised as a Schnute growth curve (Schnute 1981) rather than the von Bertalanffy curve (von Bertalanffy 1938) generally used for deepwater species. Both the von Bertalanffy curve and Schnute curve were investigated using frequentist maximum likelihood estimation (MLE) methods, as well as consideration of Bayesian von Bertalanffy and Bayesian non-parametric monotonically increasing mean length-at-age growth relationships (e.g., Dunn & Parker 2019). A total of 14 221 length and age observations were available (n = 7636 female and n = 6585 male) for west coast South Island hake, over the years 1990–2019 (Figure 27), with most of the data collected from the fishery and the remainder from surveys. Fewer ages were available from the Fisheries New Zealand database than had been previously reported because, at the time of this analysis, the most recent two years of data had not been loaded into the database. However, the amount of data available to determine the age length relationship was reasonably large, and the inclusion of the additional data is unlikely to significantly modify the estimates here.

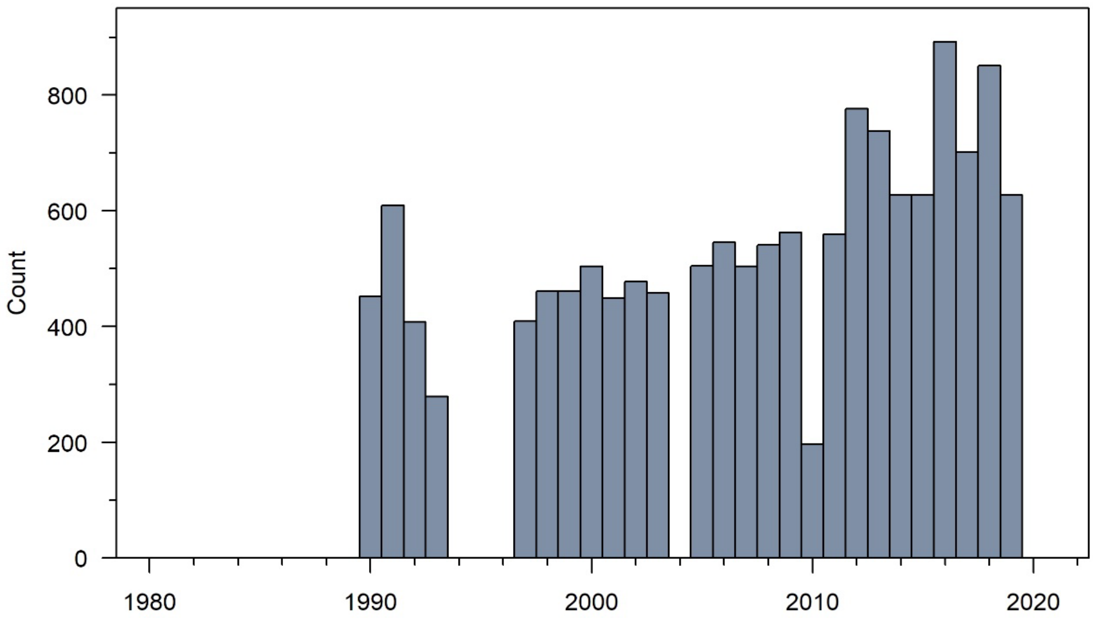

Figure 27: Number of length and age observations for west coast South Island hake by fishing year from 1979–80 to 2018–19.

Inspection of the relationship between length and age suggested approximately linear or slightly slowing growth until about age seven for males and age nine for females, with growth then slowing quickly towards a horizontal asymptote. The changes in growth up to age seven or nine for males and females, respectively, approximately corresponded to the age of 50% maturity for males and females and hence was consistent with the change from allometric growth to gonadosomatic growth as fish age and mature.

Initially, the available data for west coast South Island hake were used to estimate the growth curve parameters using maximum likelihood estimation (MLE) and Bayesian methods. The von Bertalanffy growth curve was fitted assuming normally distributed errors with a constant coefficient of variation (CV) (c) parameterised as a function of mean length. Here, the length-at-age data are assumed to consist of length (L) and age (t) observations for n fish of sex i, i.e.,

$$\bar{L}_i = L_i^{\infty}(1 - \exp(-k_i(t - t_i^0)) + \varepsilon \text{ where } \varepsilon \sim N(0, c\bar{L}_i).$$

The MLE and Bayesian von Bertalanffy growth parameters are given in Table 5, and the MLE von Bertalanffy curves and raw data are plotted in Figure 28. Diagnostic plots of the fits to all ages suggested significant departure from the normal distributional assumptions for fish aged under four, likely due to length-based selectivity effects at younger ages where juvenile sized fish were less likely to be caught or sampled, and hence the von Bertalanffy growth models were refitted using only age data for ages four and over (4+ model). The resulting growth curve was similar to that of Horn (2008) for males but resulted in a slightly higher estimate of L_{∞} for females.

Although quantile-quantile diagnostic plots for the von Bertalanffy curves suggested that there was no evidence of departure from normally distributed errors with a constant CV, the normalised residual plots by age suggested some evidence of departure of the observed mean lengths from the estimated von Bertalanffy equation (Figure 29). Plots of residuals indicated reasonable fit to the data with the age-length relationship, with small annual fluctuations in the residuals, but no apparent trend over time (Figure 30). Comparison of Schnute model fits with von Bertalanffy models did not suggest any evidence for choosing one relationship over the other, and both had similar residual diagnostics.

Model estimates of growth from both equations produced very similar relationships between length and age, and neither of these models adequately fit the length data for younger ages (i.e., under four years of age). Hence, we developed a monotonically increasing mean length-at-age model using Bayesian inference, extending the maximum likelihood mean length-at-age approach of Dunn & Parker (2019). In this model, the mean length-at-age for each age was estimated, but constrained to be monotonically increasing, with a constant CV (as a function of the mean length-at-age) with normally distributed errors.

Growth models were developed using the R package *brms* which uses Stan (Stan Development Team 2020) to sample from the posterior distribution of the von Bertalanffy model. The Bayesian von Bertalanffy model was defined as:

$$L_\infty \sim N(100, 100^2)$$
$$k \sim N(0, 100^2)$$
$$t_0 \sim N(0, 100^2)$$
$$\tau \sim N(0, 100^2)$$
$$L_t \sim N(\mu_t, \sigma^2)$$
$$\mu_t = L_\infty\left(1 - e^{-k(t-t_0)}\right)$$
$$\sigma = \tau\mu_t$$

where L_∞ is asymptotic length, k is the Brody growth coefficient, t_0 is the age at which the length is zero, μ^t is the expected length-at-age, and L_t is the predicted length-at-age.

Model selection was done using the leave-one-out information criterion (LOO IC, see Vehtari et al. 2017) which suggested that the mean length-at-age model provided a more parsimonious fit to the data than that of the Bayesian von Bertalanffy model (Table 6). Posterior predictive distributions for the mean length-at-age model showed some improvement over the Bayesian von Bertalanffy model (see Figure 31 and Figure 32). Further, the standardised residuals suggest that the mean length-at-age model fit the data better across the full range of observed ages.

However, without any constraint, the mean length-at-age model estimates of mean length (Figure 33) drifted implausibly high for the older fish when compared with the von Bertalanffy model. This suggests that the monotonic model could be improved by constraining the lengths of older fish where there were few data.

In conclusion, however, there was little difference between the resulting growth curves; the estimates of mean size-at-age and variation about these estimates that resulted from the MLE von Bertalanffy, Bayesian von Bertalanffy, and the mean length-at-age models were very similar and would be very unlikely to result in different outcomes from the choice of curve in a stock assessment.

Table 5: Revised growth parameters (MLE von Bertalanffy, MLE Schnute, and Bayesian von Bertalanffy) for west coast South Island hake.

Growth curve	Sex	Parameter (units)	Horn (2008)	All ages	MLE Ages 4+	Bayesian Ages 4+
von Bertalanffy	Male	L_∞ (cm)	82.3	83.9	85.2	83.1
		k (y^{-1})	0.357	0.329	0.228	0.329
		t_0 (y)	0.11	-0.47	-2.93	-0.43
		CV	–	0.09	0.08	0.07
	Female	L_∞ (cm)	99.6	108.8	112.2	107.0
		k (y^{-1})	0.280	0.192	0.149	0.192
		t_0 (y)	0.08	-1.03	-2.50	-0.98
		CV	–	0.09	0.08	0.10

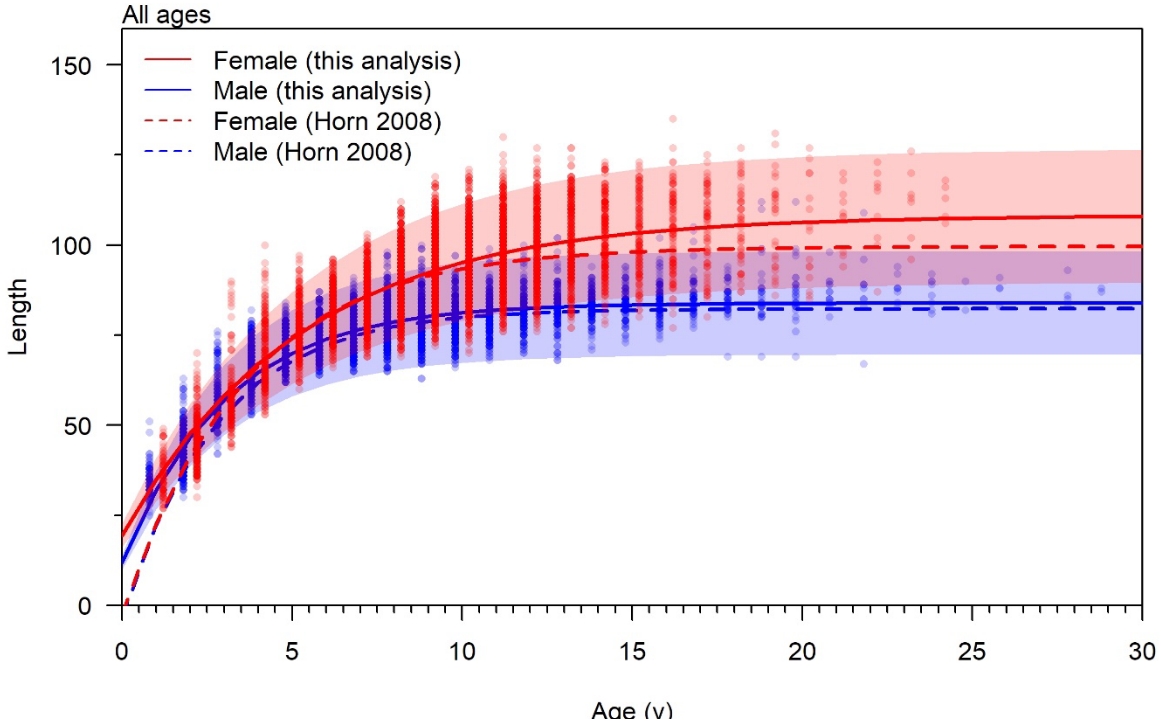

Figure 28: MLE von Bertalanffy growth curves for males (blue) and females (red) for west coast South Island hake, with points showing the observations of age-at-length for males (blue points, offset by -0.2 years) and females (red points, offset by +0.2 years). Shaded regions show 95% confidence intervals.

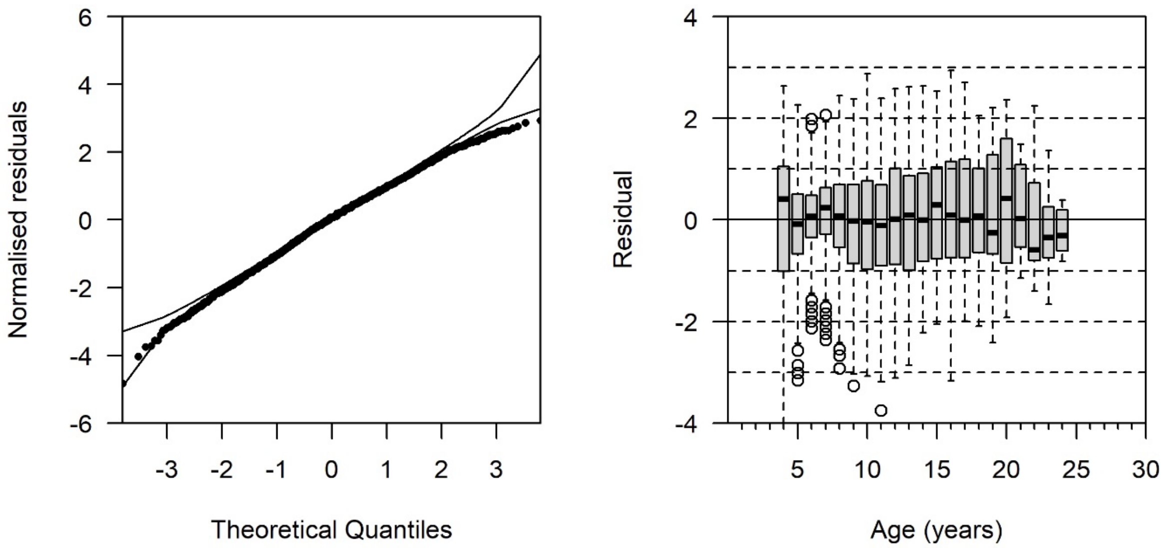

Figure 29: Diagnostic plots for the MLE von Bertalanffy growth curves for male and female hake: (left) quantile-quantile plot of normalised residuals with 95% confidence envelopes; and (right) boxplot of the normalised residuals by age.

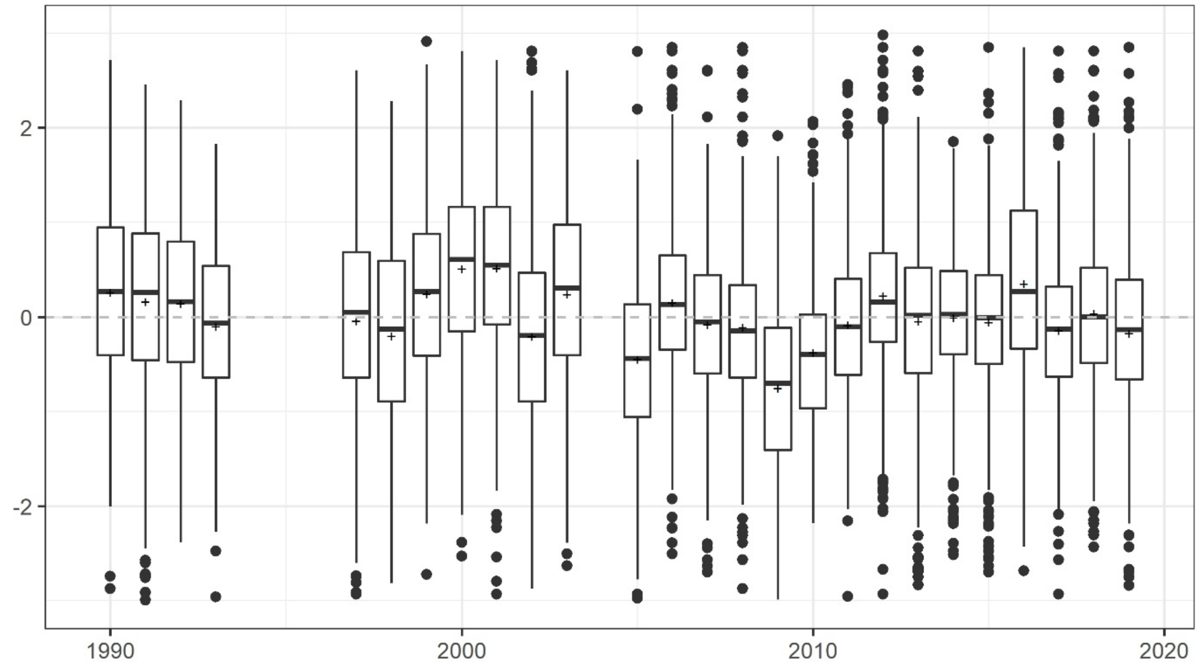

Figure 30: Boxplots of residuals (dark line = median; grey box = interquartile range; and values more than 1.5 times the interquartile range plotted as black circles) by fishing year (1989–90 to 2018–19), of the fitted von Bertalanffy growth relationship for west coast South Island hake, with the residuals for both sexes combined.

Table 6: The leave-one-out information criterion (LOO IC) for the Bayesian von Bertalanffy and mean length-at-age models (lower LOO IC suggests a more parsimonious model).

	LOO IC	
Model	Female	Male
Bayes von Bertalanffy	80 173.2	53 498.9
Mean length-at-age	79 532.6	45 769.9

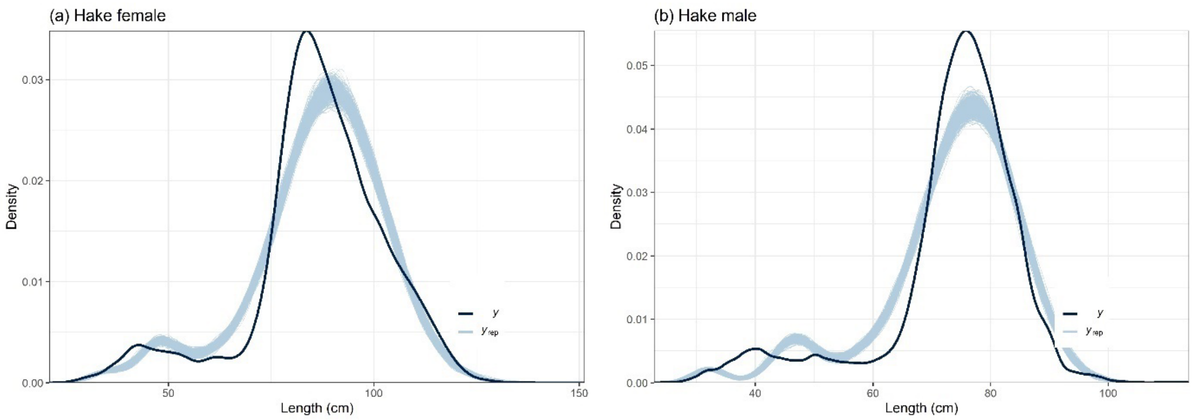

Figure 31: Comparison of the empirical distribution of the data (y) to the posterior predictive distributions of simulated data (y_{rep}) from the Bayesian von Bertalanffy growth model for (a) females and (b) males.

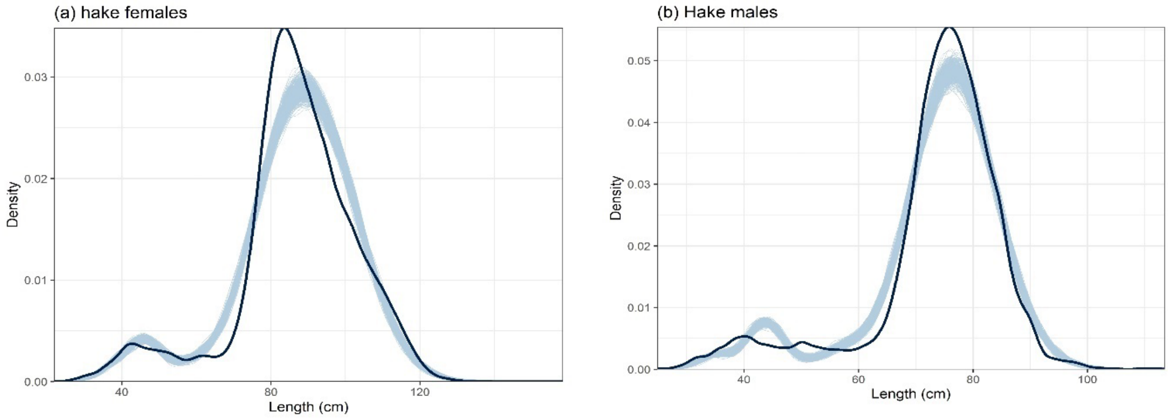

Figure 32: Comparison of the empirical distribution of the data (y) to the posterior predictive distributions of simulated data (y_{rep}) from the mean length-at-age growth model for (a) females and (b) males.

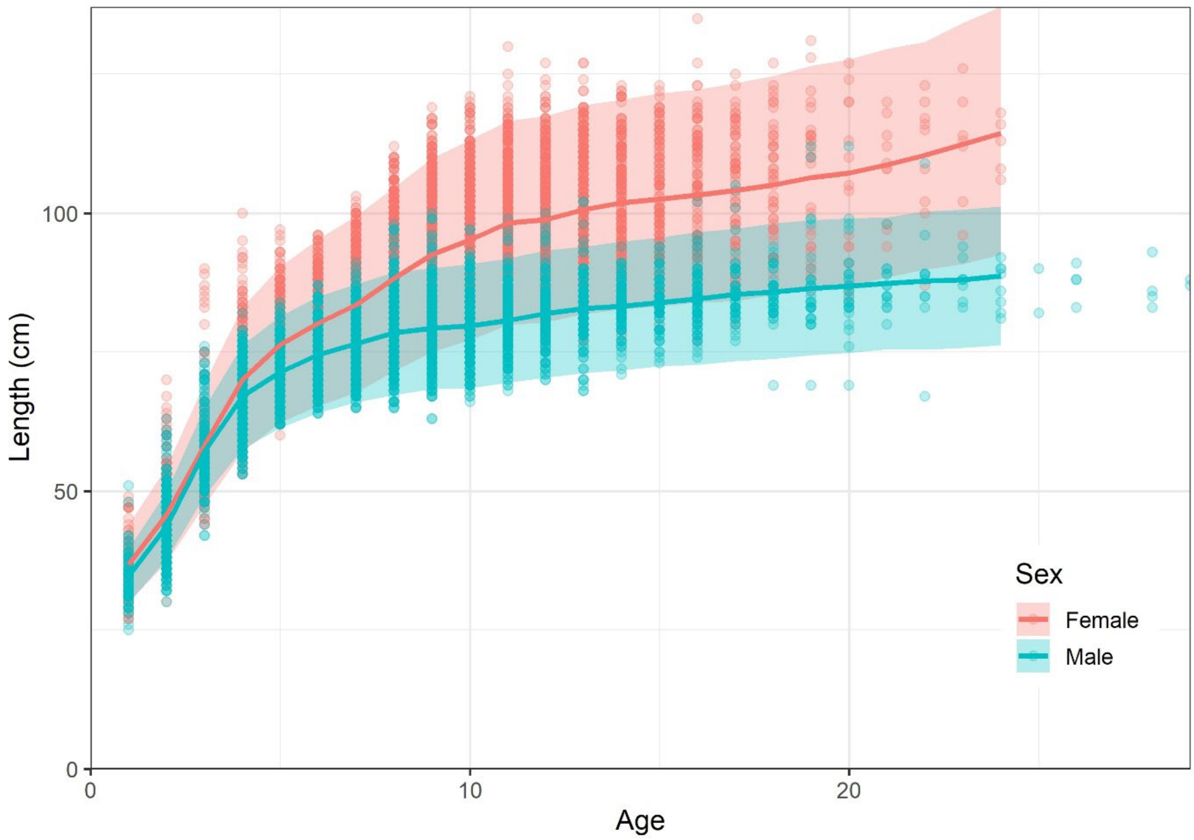

Figure 33: Estimated relationship between length and age from the Bayesian mean-length-at-age model for males (blue) and females (red) for west coast South Island hake, with points showing the observations of age-at-length for males (blue points) and females (red points). Shaded regions show 95% confidence intervals.

5. CPUE ANALYSES

5.1 Methods

Standardised CPUE indices were generated for west coast South Island hake following the method described by Ballara (2018). CPUE indices were calculated for the tow-by-tow data (HOK/HAK/LIN target TCEPR and ERS-trawl tows) using generalised linear models and stochastic partial differential equations (SPDE) models. Effort data from catch-effort data other than TCEPR and ERS-trawl data were ignored as these comprised of less than 1% of the total recorded catch of hake on the west coast South Island.

Unstandardised CPUE indices were calculated as the mean of catch (t) per tow for the tow-by-tow data. Standardised indices were calculated using a lognormal and a binomial model, where positive (i.e., non-zero) observations were modelled using a lognormal model and the proportion of zero to non-zero observations modelled as a binomial. The lognormal and binomial models were then combined using the delta-lognormal method to calculate the CPUE index using the approach of Vignaux (1994).

Models were run using forward stepwise multiple regression (Chambers & Hastie 1991) implemented in R (R Core Team 2021) using a similar approach as used by Finucci (2019) for west coast South Island hake in the previous analyses. The stepwise regression iteratively added terms to a base model initialised with *fishing year* only, where the addition of a term resulted in a reduction in residual deviance of at least 1%. Model fits were investigated using standard residual diagnostics and plots. For each model, a plot of residuals against fitted values and quantile-quantile plots were evaluated to check for departures from model assumptions. Influence plots (Bentley et al. 2012) were made for each accepted variable in the CPUE standardisation, which show the effect of each variable on the standardisations and the annual influence of each variable.

In addition to the standard GLM approach, an alternative model was investigated that used SPDE models to account for any potential spatial-temporal interactions. The SPDE models used the same covariates as determined for the standard GLM analysis with the inclusion of the 2-D spatial mesh implemented using INLA (Lindgren & Rue 2015).

Tow-by-tow CPUE indices were estimated using TCEPR and ERS-trawl data; the dependent variable catch (t) and explanatory variables are given in Table 7. These included variables for *fishing year*, *vessel*, *tow duration*, characteristics of the *gear*, and spatial variables such as the *longitude* and *latitude*, spatial *grid cell* (0.5° cells), and the west coast South Island subarea from Horn (2013a).

The explanatory variables were classified as either categorical or continuous. *Fishing year* was treated as a categorical value to derive an annual index from the CPUE indices over the years of the model. For the indices, CVs were calculated from the standard error, and 95% confidence intervals were also calculated for each index.

Categorical variables were modelled as factors in the analysis, and continuous variables were modelled as third-order polynomials. *Vessel* was included to account for potential differences in fishing efficiency between vessels and was assumed to be a constant effect over time. *Target*, *gear characteristics*, and *depth* were used to account for potential differences in the fishing efficiency of the gear or other operational aspects related to depth or the reported target species. Spatial covariates were used to allow for potential differences between locations, and these were also assumed to be constant over time.

Models using natural smoothers were also investigated for continuous variables (instead of third-order polynomials) and using Generalised Additive Models (GAM, Wood 2017) rather than GLMs. The pattern of coefficients estimated for the continuous variables were essentially the same shape and the resulting CPUE indices were similar, and hence were not further considered here.

Analysis was conducted on a subset of all data defined by 'core' set of data, i.e., the subset that comprised vessels with a consistent presence in the fishery, using a consistent method, over a consistent area. The definition of the core data was all effort recorded on TCEPR or ERS-trawl forms from bottom trawl tows from vessels with length > 28 m (to ensure consistency between the TCEPR data and ERS-trawl data); effort that targeted either hoki, hake, or ling; fished in Statistical Areas 033, 034, 035, and 703; and had reported a minimum of 20 tows in each year. Tows that reported a total catch of over 50 t; reported a bottom depth outside the range between 250 and 1200 m; or had a total event duration less than 0.2 hours or greater than 20 hours were excluded to remove reporting errors and potential outliers. In addition, vessels that had been identified as a vessel that misreported catch were also excluded. The core vessel data set was then created from all those vessels with a presence of at least five years in the fishery (comprising 90% of the total reported catch). This resulted in a data set comprising 77 unique vessels (Figure 34), and the relative contribution of effort in each year of each vessel is shown in Figure 35.

Table 7: Description of variables used for the west coast South Island hake CPUE analysis for the tow-by-tow data. Continuous variables were fitted as third order polynomials.

Variable	Type	Description
Year	Categorical	Fishing year
Vessel	Categorical	Vessel identification number
Statistical area	Categorical	Statistical area
Tow duration	Continuous	Duration of tow (h)
Catch	Continuous	Estimated green weight of hake (t) caught
Target species	Categorical	Target species (HOK/HAK/LIN)
Date	Continuous	Start date of the tow
Month	Categorical	Month of the year
Day of year	Continuous	Day of the year, starting at 1 January
Time start	Continuous	Start time of tow
Time mid	Continuous	Time at the midpoint of the tow
Method	Categorical	Fishing gear (BT = bottom trawl; MB = midwater trawl within 5 m of the seabed; MW = midwater trawl)
Tow distance	Continuous	Distance of tow (km)
Distance (duration)	Continuous	Distance of tow (calculated as speed in knots × duration)
Headline height	Continuous	Headline height (m) of the net
Bottom depth	Continuous	Seabed depth (m)
Net depth	Continuous	Net depth (m) (i.e., depth of ground rope)
Speed	Continuous	Vessel speed (knots)
Vessel experience	Continuous	Number of years the vessel has been involved in the fishery
Twin trawl	Categorical	T/F variable for a vessel that has used twin trawl
Subarea	Categorical	Defined by fishing effort distribution and depth
Longitude	Continuous	Longitude
Latitude	Continuous	Latitude
Grid number	Categorical	0.5° square based on start latitude and longitude

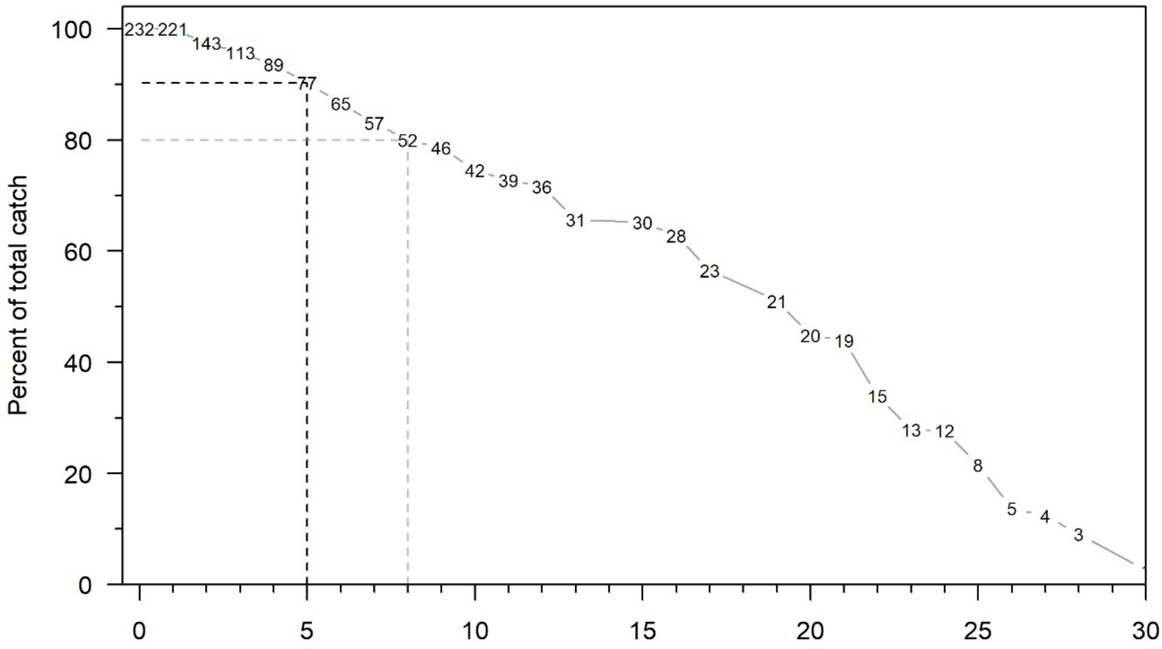

Figure 34: Percentage of catch for different numbers of years in the fishery used to determine core vessels in the tow-by-tow CPUE standardisation for the west coast South Island. Dashed lines indicate the effect of selecting the years in the fishery for core vessels that give 90% of total catch (77 vessels) or 80% of total catch (52 vessels).

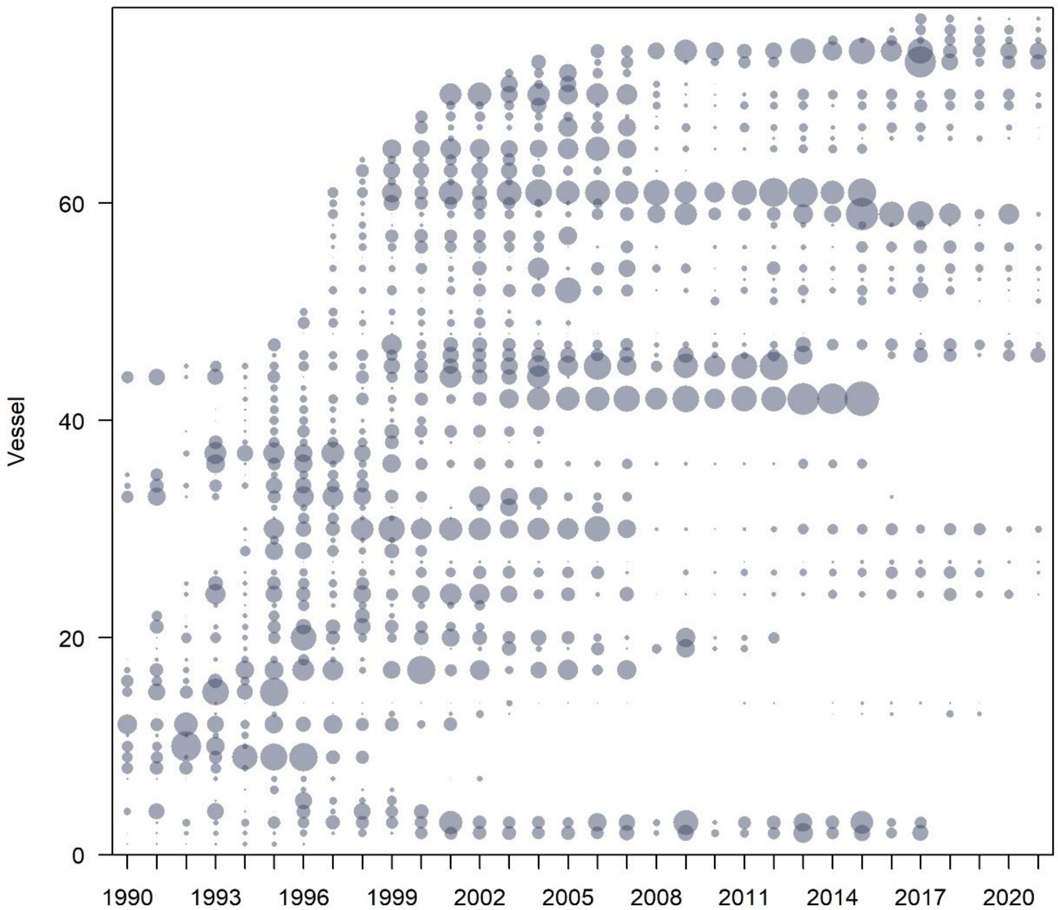

Figure 35: Relative effort by vessel and fishing year for the core data used in the tow-by-tow CPUE standardisation, for the west coast South Island for 1989–90 to 2020–21.

5.2 Results

The model terms accepted into the lognormal GLM CPUE model for the tow-by-tow model included *year*, *target species*, *grid cell* (0.5° cell), *vessel*, and *month*. The model had an r^2 of 42% (Table 8). The standardised lognormal CPUE indices suggested a decline in relative abundance (Table 9) up to about 2015 and a small increase after and were similar to the lognormal indices obtained by Finucci (2019). The model terms accepted into the binomial CPUE model for the tow-by-tow model were similar and included *year*, *grid cell* (0.5° cell), *vessel*, *target species*, and *bottom depth*. The model had an r^2 of 28% (Table 10). The binomial indices fluctuated for most of the series before reducing to a low in about 2017, and then increasing again, before declining in recent years. The effect of the binomial on the overall index was to moderate the changes observed in the lognormal indices.

The combined index is given in Table 9 and Figure 36. Trends in the combined indices were similar to that reported by Finucci (2019) for the period where these indices overlapped, but both were different in pattern to the observed trend in the trawl survey biomass index over the same period.

For both the lognormal and the binomial models, the residual plots were adequate. Influence plots for the lognormal model indicated that changes in *target species* (Figure 37), *vessel* (Figure 38), *fishing depth* (Figure 39), and *longitude* (Figure 40) correspond to a significant change in the influence on the index in the mid-2000s.

In the tow-by-tow CPUE indices, the variable describing the use of twin trawls was not selected as significant; however, additional analyses were undertaken that excluded twin trawls to evaluate the sensitivity of resulting CPUE indices. The use of twin trawls has been reported on the catch and effort forms since 2009, but only a low proportion of the hake catch in the tow-by-tow data was reported as being from a twin trawl. The resulting lognormal, binomial, and combined indices excluding twin trawl data were almost identical to the combined tow-by-tow CPUE indices that included twin trawls.

Analyses using lognormal SPDE models provided very similar annual indices from the catch and effort data as the lognormal GLM analysis (Figure 41), as did indices based on GAM using natural smoothers for the continuous variables.

The bottom trawl standardised CPUE indices for hake fluctuated higher in the late 1990s, then declined to a low in 2008, before fluctuating up again in 2012 and then declining thereafter. However, the tow-by-tow CPUE is less optimistic in the most recent years, decreasing slightly. However, the pattern of change in the mid-2000s more likely mirrored the changes in the annual catch of hoki, the dominant target species off the west coast South Island, rather than the relative abundance of hake. The GLM and SPDE trends were similar, indicating the GLM did an adequate job of capturing spatial trends if there were any. Neither the GLM nor SPDE indices were similar to the patterns in the trawl survey series for west coast South Island hake.

Diagnostic plots of the indices were similar for each of the models and did not suggest strong evidence of departure from model assumptions. Interpretation of the changes that may have occurred in reporting with the introduction of the ERS-trawl forms introduces a potential confounding factor into the interpretation of the indices. In particular, vessels that only reported on the TCEPR forms are now included with all trawl vessels. Sub-setting the data to those with a recorded length of > 28 m reduces the influence of additional vessels on the analysis, as does the choice of a long period of presence in the data.

Table 8: The parameters included into the lognormal tow-by-tow CPUE model, degrees of freedom (df) for each variable, log-likelihood, AIC, and r^2 value with the addition of each term.

	Term	df	Residual deviance	AIC	r^2
1	Intercept	1	–	–	–
2	*Year*	31	181 074	273 553	0.04
3	*Vessel*	76	144 562	257 265	0.23
4	*Target*	1	124 595	246 416	0.34
4	*Longitude*	3	117 129	241 911	0.38
5	*Fishing duration*	3	111 780	238 505	0.40
6	*Fishing depth*	3	108 428	236 288	0.42

Table 9: Lognormal, binomial, and combined indices (with 95% confidence intervals and CV) for the tow-by-tow GLM CPUE index 1990–2021.

	Lognormal		Binomial		Combined	
Year	Index (95% CIs)	CV	Index (95% CIs)	CV	Index (95% CIs)	CV
1990	0.63 (0.58–0.70)	0.08	0.96 (0.91–1.02)	0.02	0.61 (0.30–0.91)	0.08
1991	1.25 (1.13–1.37)	0.04	0.74 (0.69–0.79)	0.02	0.92 (0.62–1.22)	0.04
1992	0.58 (0.53–0.65)	0.09	0.56 (0.51–0.61)	0.03	0.32 (0.00–0.65)	0.09
1993	1.14 (1.04–1.25)	0.04	0.55 (0.51–0.59)	0.03	0.62 (0.35–0.90)	0.05
1994	0.92 (0.84–1.00)	0.05	0.48 (0.44–0.52)	0.02	0.44 (0.18–0.70)	0.05
1995	1.47 (1.37–1.58)	0.02	0.82 (0.78–0.85)	0.01	1.19 (0.97–1.42)	0.03
1996	1.61 (1.51–1.73)	0.02	1.01 (0.98–1.05)	0.01	1.63 (1.41–1.84)	0.02
1997	1.38 (1.29–1.47)	0.02	0.99 (0.96–1.03)	0.01	1.36 (1.15–1.57)	0.03
1998	1.10 (1.04–1.17)	0.03	1.05 (1.02–1.08)	0.01	1.15 (0.96–1.35)	0.03
1999	1.20 (1.12–1.27)	0.03	0.89 (0.86–0.93)	0.01	1.06 (0.86–1.26)	0.03
2000	1.27 (1.20–1.35)	0.02	1.00 (0.97–1.03)	0.01	1.27 (1.07–1.46)	0.03
2001	0.93 (0.88–0.98)	0.03	0.98 (0.95–1.01)	0.01	0.91 (0.72–1.09)	0.03
2002	1.35 (1.27–1.43)	0.02	1.09 (1.06–1.11)	0.01	1.45 (1.27–1.64)	0.02
2003	1.09 (1.03–1.15)	0.03	1.07 (1.04–1.10)	0.01	1.16 (0.98–1.34)	0.03
2004	1.01 (0.96–1.08)	0.03	1.11 (1.08–1.14)	0.01	1.12 (0.94–1.31)	0.03
2005	0.94 (0.88–1.00)	0.04	0.92 (0.88–0.96)	0.01	0.86 (0.64–1.07)	0.04
2006	0.76 (0.71–0.81)	0.04	1.00 (0.97–1.04)	0.01	0.76 (0.55–0.96)	0.04
2007	0.69 (0.64–0.75)	0.06	0.82 (0.77–0.87)	0.02	0.56 (0.31–0.82)	0.06
2008	0.43 (0.40–0.47)	0.09	0.91 (0.86–0.96)	0.02	0.39 (0.14–0.64)	0.09
2009	0.70 (0.64–0.76)	0.06	0.94 (0.89–0.99)	0.02	0.65 (0.38–0.92)	0.06
2010	0.69 (0.63–0.75)	0.06	0.95 (0.90–0.99)	0.02	0.65 (0.39–0.91)	0.06
2011	0.92 (0.86–0.99)	0.04	1.27 (1.24–1.30)	0.01	1.16 (0.94–1.38)	0.04
2012	1.22 (1.13–1.31)	0.03	1.11 (1.08–1.15)	0.01	1.35 (1.12–1.57)	0.03
2013	1.37 (1.28–1.47)	0.02	1.17 (1.14–1.20)	0.01	1.59 (1.38–1.81)	0.03
2014	0.92 (0.86–0.98)	0.04	1.12 (1.08–1.15)	0.01	1.02 (0.80–1.23)	0.04
2015	1.17 (1.10–1.24)	0.03	1.20 (1.17–1.23)	0.01	1.39 (1.20–1.59)	0.03
2016	1.16 (1.08–1.24)	0.03	1.20 (1.17–1.22)	0.01	1.37 (1.17–1.58)	0.03
2017	1.06 (1.00–1.13)	0.03	1.26 (1.24–1.29)	0.01	1.33 (1.14–1.52)	0.03
2018	0.93 (0.88–0.99)	0.03	1.36 (1.34–1.38)	0.01	1.26 (1.07–1.45)	0.03
2019	0.83 (0.78–0.90)	0.04	1.19 (1.15–1.22)	0.01	0.98 (0.76–1.21)	0.04
2020	0.82 (0.76–0.88)	0.04	1.17 (1.13–1.20)	0.01	0.95 (0.72–1.18)	0.05
2021	0.46 (0.42–0.50)	0.09	1.11 (1.07–1.15)	0.01	0.51 (0.25–0.77)	0.09

Table 10: The parameters included into the binomial tow-by-tow GLM CPUE model, degrees of freedom (df) for each variable, residual deviance, AIC, and r^2 value with the addition of each term.

	Term	df	Residual deviance	AIC	r^2
1	Intercept			–	–
2	*Year*	31	133 130	177 369	0.03
3	*Fishing depth*	3	133 127	145 884	0.21
4	*Longitude*	3	133 124	138 685	0.24
5	*Vessel*	76	133 048	132 351	0.28

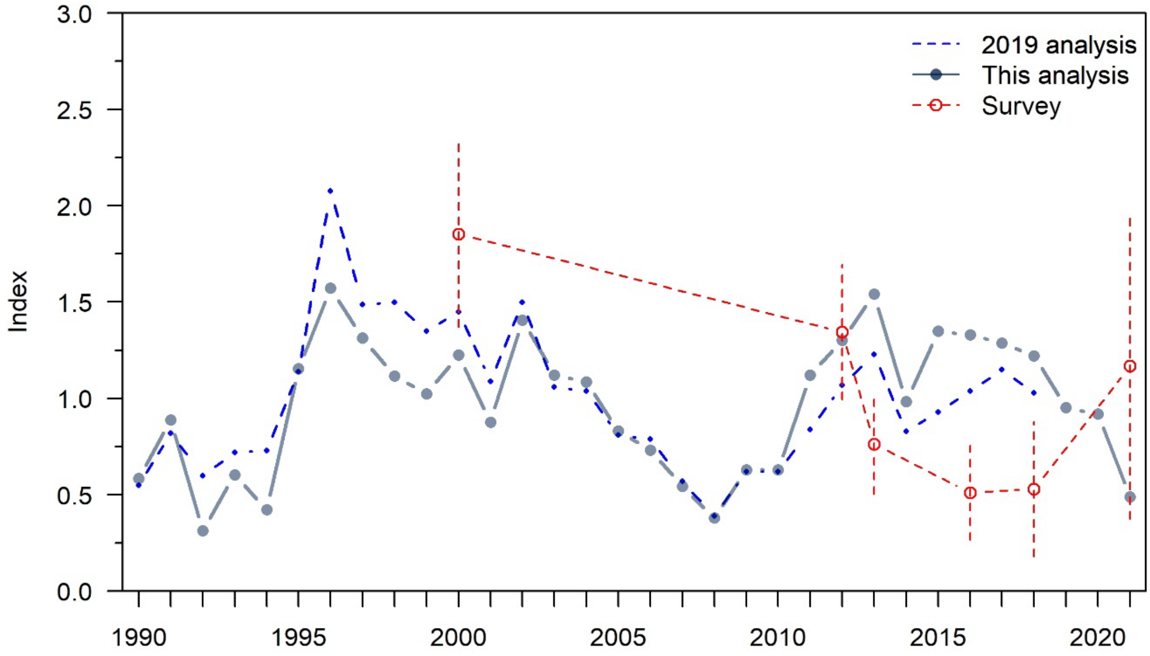

Figure 36: Combined CPUE indices for the tow-by-tow analysis (this analysis), compared with the analysis of Finucci (2019) (2019 analysis), and for the west coast South Island trawl survey biomass index (survey) by fishing year, from 1990–91 to 2020–21.

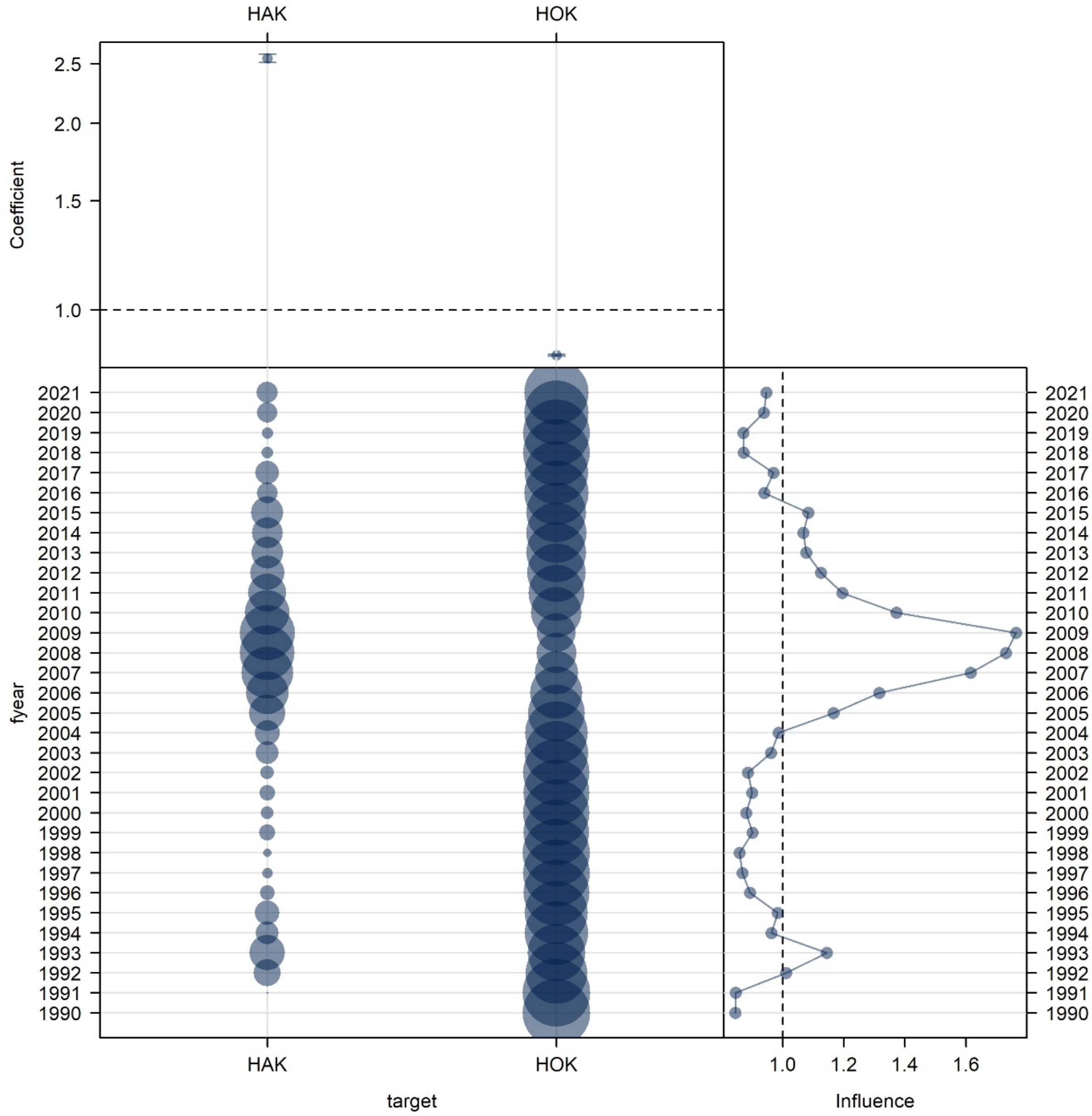

Figure 37: Influence plots of the effect of target species on the lognormal CPUE indices for the tow-by-tow analysis.

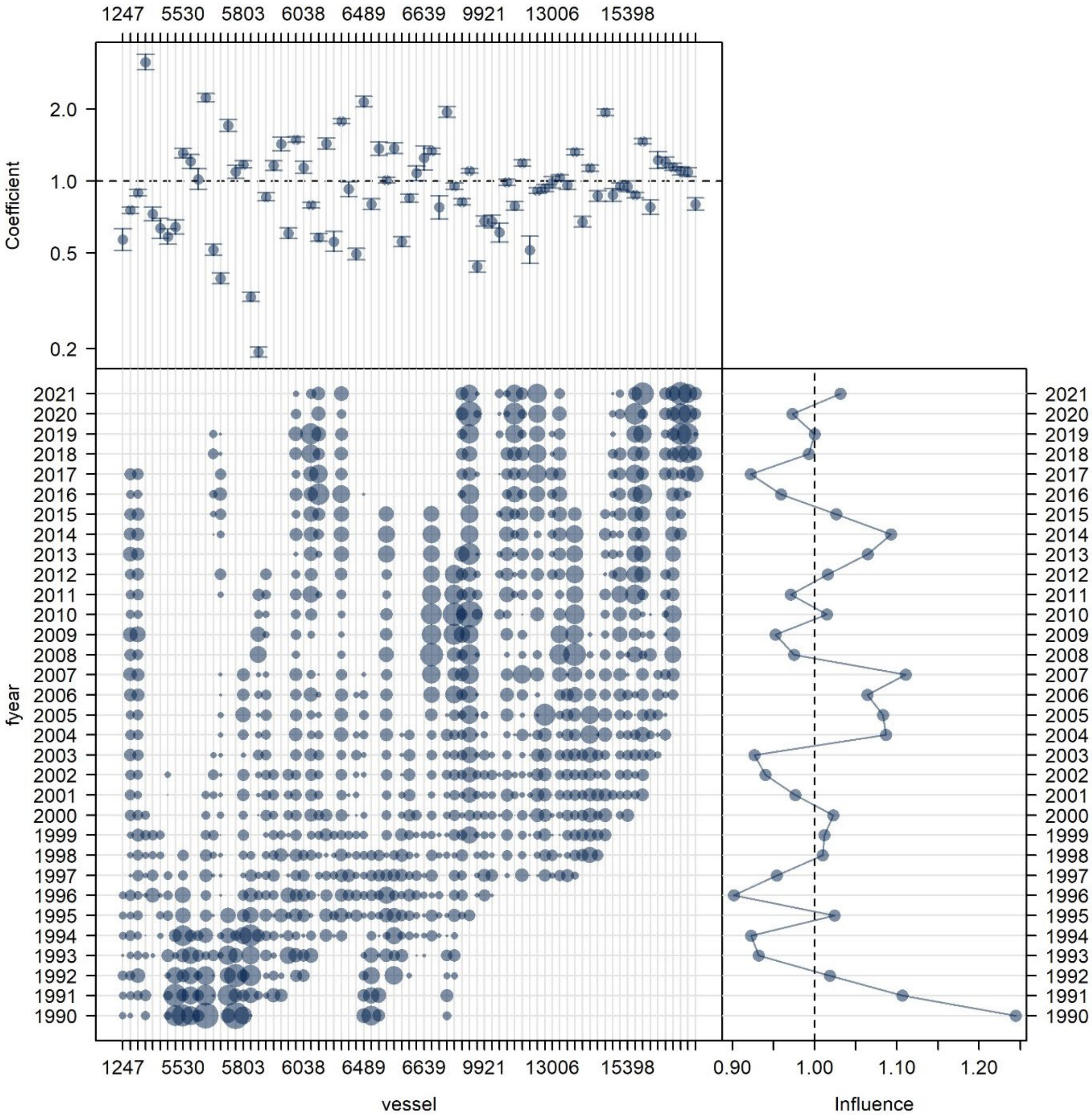

Figure 38: Influence plots of the effect of Vessel on the lognormal CPUE indices for the tow-by-tow analysis.

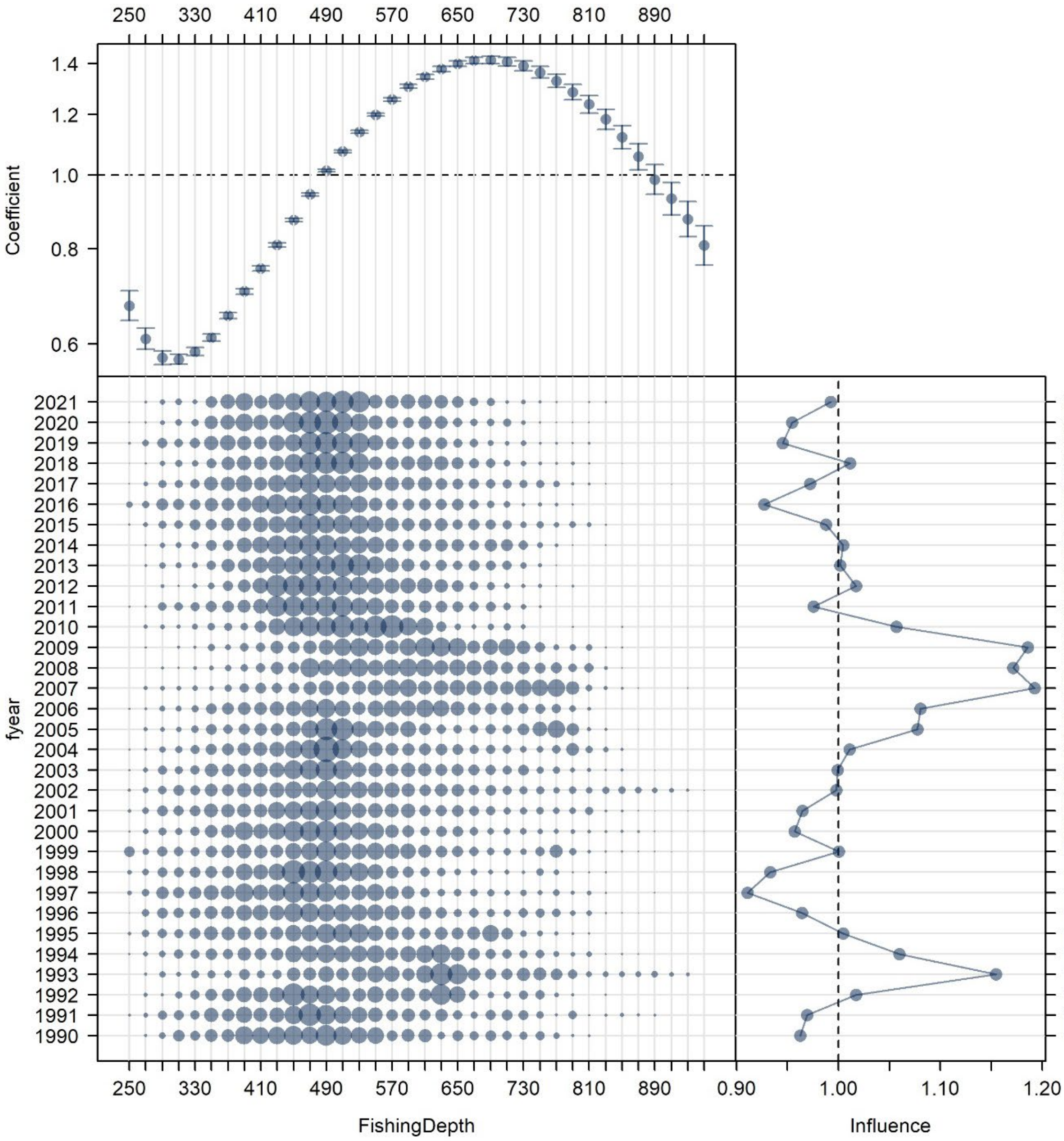

Figure 39: Influence plots of the effect of Fishing depth (m) on the lognormal CPUE indices for the tow-by-tow analysis.

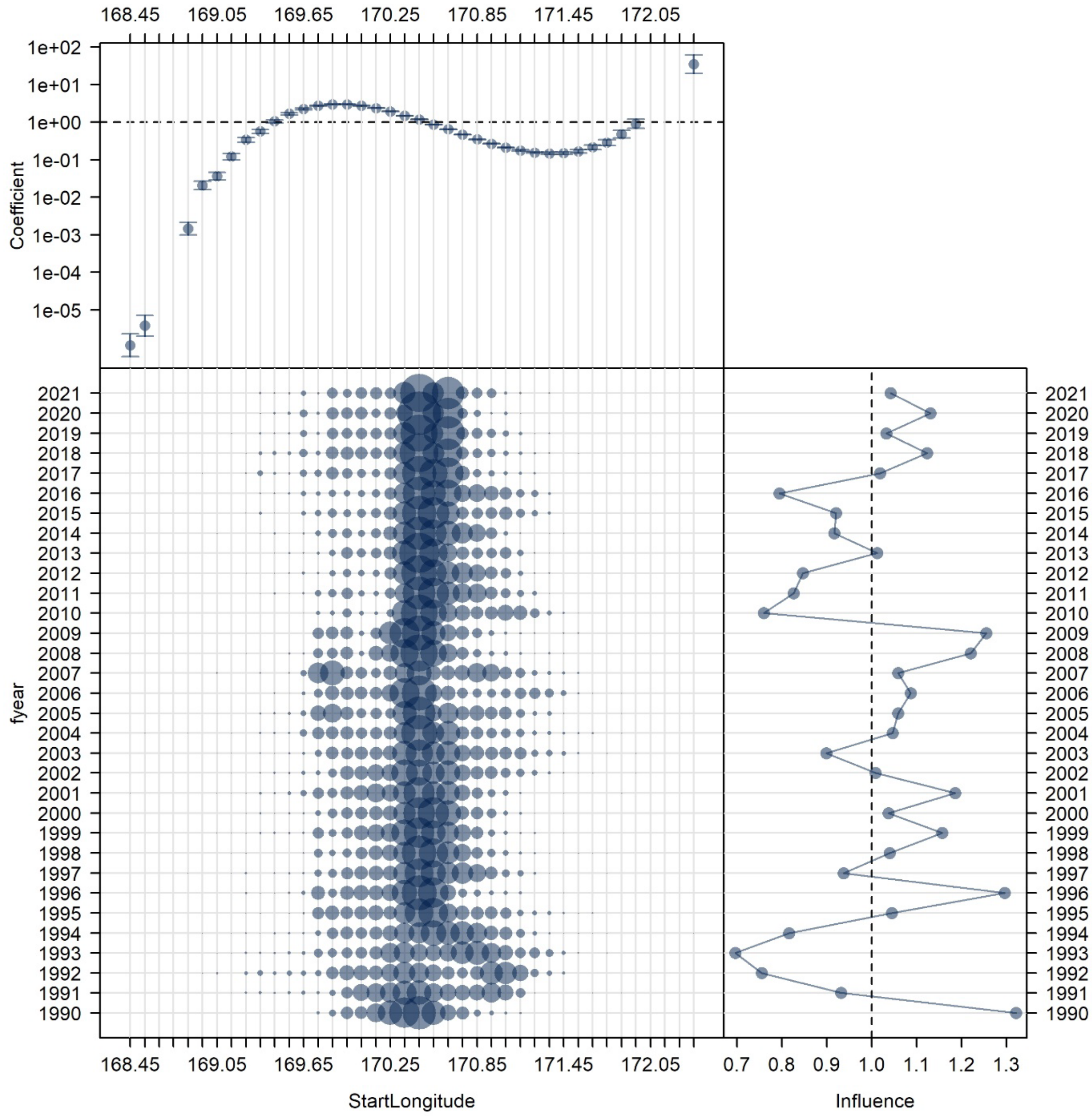

Figure 40: Influence plots of the effect of longitude (° E) on the lognormal CPUE indices for the tow-by-tow analysis.

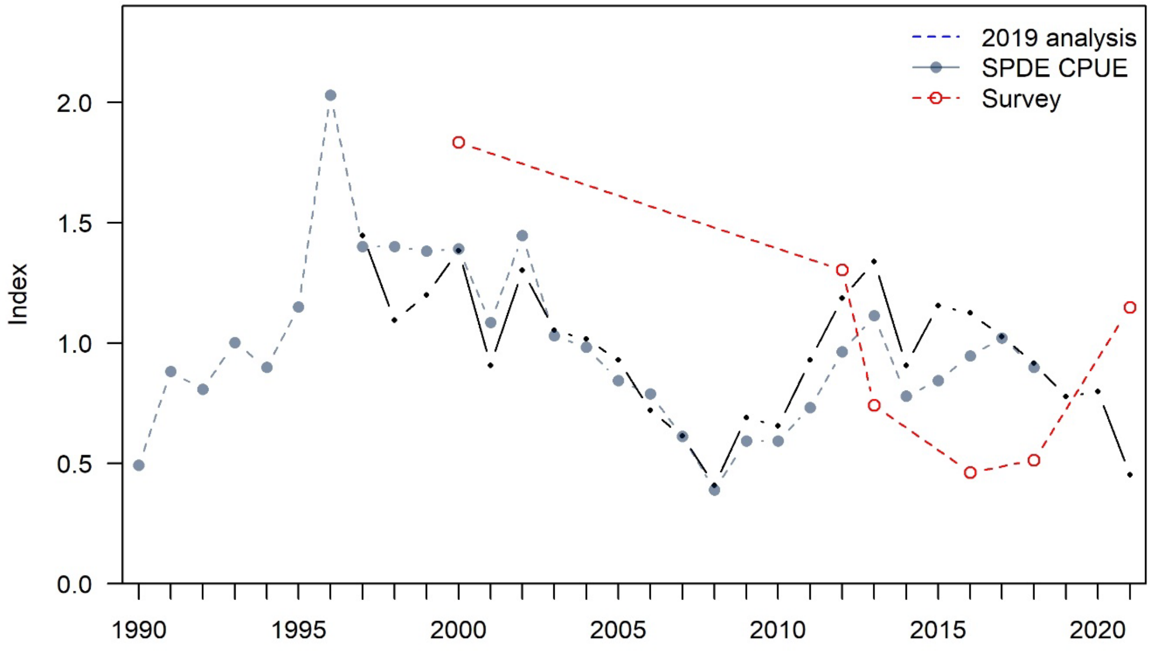

Figure 41: Lognormal SPDE CPUE indices for the tow-by-tow analysis (SPDE CPUE), compared with the analysis of Finucci (2019) (2019 analysis), and for the west coast South Island trawl survey (survey) biomass index by fishing year, from 1990–91 to 2020–21.

6. DISCUSSION

The population structure and life cycle of hake off the west coast South Island is not well known. Previous analyses showed that the length frequencies of hake were different between the west coast and both the Chatham Rise and the Sub-Antarctic. The growth parameters were also different between the three areas (Horn 1997) and juvenile hake are found in all three areas (Hurst et al. 2000). Analysis of morphometric data from the 1990s (Colman, NIWA, unpublished data) showed little difference between hake on the Chatham Rise and those off the east coast of the North Island, but significant differences between Chatham Rise hake and those from the Sub-Antarctic, Puysegur, and off the west coast of the South Island.

However, hake off the west coast South Island, while likely a separate stock, exhibit an unusual length and age structure. On the Chatham Rise and the Sub-Antarctic, hake of all lengths and ages are seen in the population, while on the west coast South Island hake that are immediately pre-mature in size are rarely seen. The absence of sub-adult fish has been noted in previous analyses (e.g., Horn 2011), but a hypothesis of a stock structure that explains the age and length observations has not previously been proposed.

Juvenile hake, at sizes up to about 60 cm, are often observed in both shallow and deep water during winter off the west coast South Island. These juvenile sized fish are sometimes also observed intermingled in depth ranges where most of the adult and mature sized hake are caught. In addition, immediately pre-mature sized fish (about 65 cm in length) are rarely observed in the commercial length frequency data and trawl survey data, with most fish being of a size consistent with estimates of the size-at-maturity. When these sub-adult fish are observed, they have been seen in low numbers in orange roughy tows at the edge of the New Zealand EEZ on the western side of the Challenger Plateau.

Without direct observations of the sub-adult hake from the west coast South Island and outside the winter months, any stock structure hypothesis remains speculative. However, a plausible stock structure hypothesis is that hake juveniles reside year-round off the west coast South Island, and, as they grow and reach a size of about 50–60 cm, they require prey of a larger size and hence the sub-adults move and disperse onto the Challenger Plateau and possibly towards Puysegur. As adults, the larger mature-sized hake may then follow hoki to the west coast South Island during the hoki spawning migration, to feed and then spawn at the end of the season. During this time, juvenile hake (less than 65 cm) are 'displaced' by the larger adult hake and move shallower, deeper, and/or to the north away from the adult hake, forming clusters of juvenile sized hake dispersed outside the areas where the larger hake are found. Further research on the age structure of hake off the west coast South Island, specifically the presence of sub-adult fish, and the age structure during period of the year other than winter would improve the data available to develop and test stock structure and life cycle hypotheses for west coast South Island hake.

Analyses of the spatial temporal pattern of hake off the west coast South Island suggests that there are a number of changes that are confounded with the pattern of fishing operations, and standardised catch rates are likely strongly influenced by the market value of hake, hoki catch availability, and the distribution of the fleet with respect to the hake and dominant hoki target population off the west coast South Island in any given year. CPUE indices were deemed unlikely to be an index of relative abundance of hake, and they more likely reflected changes in the annual catch of hoki off the west coast South Island. Trends in the CPUE indices were quite dissimilar to the patterns in the trawl survey over the equivalent period. However, we note that neither the survey nor the CPUE may adequately monitor hake in and south of the Hokitika Canyon. CPUE data from that area were more sparse and bottom trawling in those areas is difficult due to the terrain.

7. ACKNOWLEDGEMENTS

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9. APPENDIX A: RESOURCE SURVEY BIOMASS INDICES FOR HAKE

Table 11: Biomass indices (t) and coefficients of variation (CV) for hake from resource surveys of the Sub-Antarctic. (Estimates assume that the areal availability, vertical availability, and vulnerability are equal to one.) (Continued on next two pages)

Vessel	Date	Series	Trip code	Depth	Notes	Biomass	CV	Reference
Wesermünde	Mar–May 1979	Autumn	–	–	*1*			(Kerstan & Sahrhage 1980)
Wesermünde	Oct–Dec 1979	Summer	–	–	*1*			(Kerstan & Sahrhage 1980)
Shinkai Maru	Mar–Apr 1982	Autumn	SHI8201	200–800 m		6 045	0.15	(Horn 2017)
Shinkai Maru	Oct–Nov 1983	Summer	SHI8303	200–800 m		11 282	0.22	(Horn 2017)
Amaltal Explorer	Oct–Nov 1989	Summer	AEX8902	200–800 m		2 660	0.21	(Livingston & Schofield 1993)
Amaltal Explorer	Jul–Aug 1990	Winter	AEX9001	300–800 m	*2*	4 343	0.19	(Hurst & Schofield 1995)
Amaltal Explorer	Nov–Dec 1990	Summer	AEX9002	300–800 m	*3*	2 460	0.16	(Horn 2017)
Tangaroa	Nov–Dec 1991	Summer	TAN9105	Reported	*4*	5 686	0.43	(Chatterton & Hanchet 1994)
				300–800 m	*5*	5 553	0.44	(O'Driscoll & Bagley 2001)
				1991 area	*2*	5 686	0.43	(O'Driscoll & Bagley 2001)
				1996 area		–	–	*Not surveyed*
Tangaroa	Apr–May 1992	Autumn	TAN9204	Reported	*4*	5 028	0.15	(Schofield & Livingston 1994a)
				300–800 m	*3*	5 028	0.15	(O'Driscoll & Bagley 2001)
				1991 area	*5*	–	–	*Not surveyed*
				1996 area		–	–	*Not surveyed*
Tangaroa	Sep–Oct 1992	September	TAN9209	Reported	*4*	3 762	0.15	(Schofield & Livingston 1994b)
				300–800 m		–	–	*Not surveyed*
				1991 area	*3*	3 760	0.15	(O'Driscoll & Bagley 2001)
				1996 area		–	–	*Not surveyed*
Tangaroa	Nov–Dec 1992	Summer	TAN9211	Reported	*4*	1 944	0.12	(Ingerson et al. 1995)
				300–800 m	*5*	1 822	0.12	(O'Driscoll & Bagley 2001)
				1991 area	*2*	1 944	0.12	(O'Driscoll & Bagley 2001)
				1996 area		–	–	*Not surveyed*
Tangaroa	May–Jun 1993	Autumn	TAN9304	Reported	*4*	3 602	0.14	(Schofield & Livingston 1994c)
				300–800 m	*3*	3 221	0.14	(O'Driscoll & Bagley 2001)
				1991 area		–	–	*Not surveyed*
				1996 area		–	–	*Not surveyed*
						–	–	*Not surveyed*
Tangaroa	Nov–Dec 1993	Summer	TAN9310	Reported	*2*	2 572	0.12	(O'Driscoll & Bagley 2001)
				300–800 m	*3*	2 286	0.12	(O'Driscoll & Bagley 2001)

Vessel	Date	Series	Trip code	Depth	Notes	Biomass	CV	Reference
				1991 area	*4*	2 567	0.12	(O'Driscoll & Bagley 2001)
				1996 area		–	–	*Not surveyed*
Tangaroa	Mar–Apr 1996	Autumn	TAN9605	Reported	*2*	3 946	0.16	(O'Driscoll & Bagley 2001)
				300–800 m	*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	(Bagley & McMillan 1999)
Tangaroa	Apr–May 1998	Autumn	TAN9805	Reported	*2*	2 554	0.18	(O'Driscoll & Bagley 2001)
				300–800 m	*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 et al. 2001)
Tangaroa	Nov–Dec 2000	Summer	TAN0012	300–800 m	*3*	2 194	0.17	(O'Driscoll et al. 2001)
				1991 area	*4*	2 657	0.16	(O'Driscoll et al. 2001)
				1996 area	*5*	3 103	0.14	(O'Driscoll & Bagley 2003a)
Tangaroa	Nov–Dec 2001	Summer	TAN0118	300–800 m	*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 2003b)
Tangaroa	Nov–Dec 2002	Summer	TAN0219	300–800 m	*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 2004)
Tangaroa	Nov–Dec 2003	Summer	TAN0317	300–800 m	*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 2006a)
Tangaroa	Nov–Dec 2004	Summer	TAN0414	300–800 m	*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 2006b)
Tangaroa	Nov–Dec 2005	Summer	TAN0515	300–800 m	*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 2008)
Tangaroa	Nov–Dec 2006	Summer	TAN0617	300–800 m	*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	(Bagley et al. 2009)
Tangaroa	Nov–Dec 2007	Summer	TAN0714	300–800 m	*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	(O'Driscoll & Bagley 2009)

Vessel	Date	Series	Trip code	Depth	Notes	Biomass	CV	Reference
Tangaroa	Nov–Dec 2008	Summer	TAN0813	300–800 m	*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	(Bagley & O'Driscoll 2012)
Tangaroa	Nov–Dec 2009	Summer	TAN0911	300–800 m	*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 et al. 2013)
Tangaroa	Nov–Dec 2011	Summer	TAN1117	300–800 m	*3*	1 434	0.30	(Bagley et al. 2013)
				1991 area	*4*	1 885	0.24	(Bagley et al. 2013)
				1996 area	*7*	2 004	0.23	(Bagley et al. 2014)
Tangaroa	Nov–Dec 2012	Summer	TAN1215	300–800 m	*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. 2017)
Tangaroa	Nov–Dec 2014	Summer	TAN1412	300–800 m	*3*	1 101	0.32	(Bagley et al. 2017)
				1991 area	*4*	1 477	0.25	(Bagley et al. 2017)
				1996 area	*7*	1 485	0.25	(O'Driscoll et al. 2018)
Tangaroa	Nov–Dec 2016	Summer	TAN1614	300–800 m	*3,8*	1 000	0.25	(O'Driscoll et al. 2018)
				1991 area	*4,8*	1 373	0.34	(MacGibbon et al. 2019)
				1996 area	*8*	–	–	*Not available*
Tangaroa	Nov–Dec 2018	Summer	TAN1811	300–800 m	*3*	1 354	0.28	(MacGibbon et al. 2019)
				1991 area		1 675	0.25	(MacGibbon et al. 2019)
				1996 area	*7*	1 785	0.24	MacGibbon (pers. comm)
Tangaroa	Nov–Dec 2020	Summer	TAN2014	300–800 m	*3*	1 310	0.23	MacGibbon (pers. comm)
				1991 area	*4*	1 572	0.20	MacGibbon (pers. comm)
				1996 area	*7*		–	*Not yet available*

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 the 800–1000 m strata in Puysegur region and at the Bounty Platform.
4. The biomass and CV calculated from source records using the equivalent 1991 region, which includes the 800–1000 m strata in Puysegur region but excludes the Bounty Platform strata.
5. The biomass and CV calculated from source records using the equivalent 1996 region, which includes the 800–1000 m strata in Puysegur region but excludes the Bounty Platform strata. (The 1996 region added additional 800–1000 m strata to the north and to the south of the Sub-Antarctic to the 1991 region).
6. Doorspread data not recorded for this survey. Analysis of source data with average of all other survey doorspread estimates resulted in a new estimate of biomass.
7. The biomass and CV calculated from source records using the equivalent 1996 region, which includes the 800–1000 m strata in Puysegur region but excludes the Bounty Platform strata. (The 1996 region added additional 800–1000 m strata to the north and to the south of the Sub-Antarctic to the 1991 region). However, in 2003, stratum 26 (the most southern 800–1000 m stratum) 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.
8. Due to bad weather, the core survey strata were unable to be completed in 2017; biomass estimates were scaled up based on the proportion of hake biomass in those strata in previous surveys from 2000 to 2014. This introduced additional uncertainty into the 2017 biomass estimate (see Dunn 2019). Biomass for the 1996 area was not estimated.

Table 12: Biomass indices (t) and coefficients of variation (CV) for hake from resource surveys of the Chatham Rise. (Estimates assume that the areal availability, vertical availability, and vulnerability are equal to one.) (Continued next page)

Vessel	Date	Series	Trip code	Depth	Notes	Biomass	CV	Reference
Wesermünde	Mar–May 1979	Autumn		–	*1*			(Kerstan & Sahrhage 1980)
Wesermünde	Oct Dec 1979	Spring		–	*1*			(Kerstan & Sahrhage 1980)
Shinkai Maru	Mar 1983	Autumn	SHI8301	200–800 m		11 327	0.12	(Horn 2017)
Shinkai Maru	Nov–Dec 1983	Summer	SHI8304	200–800 m	*2*	8 160	0.12	(Horn 2017)
Shinkai Maru	Jul 1986	Winter	SHI8602	200–800 m		7 630	0.13	(Horn 2017)
Amaltal Explorer	Nov–Dec 1989	Summer	AEX8903	200–800 m		3 576	0.19	(Horn 2017)
Tangaroa	Jan 1992	Summer	TAN9106	200–800 m		4 180	0.15	(Horn 1994a)
Tangaroa	Jan 1993	Summer	TAN9212	200–800 m		2 950	0.17	(Horn 1994b)
Tangaroa	Jan 1994	Summer	TAN9401	200–800 m		3 353	0.10	(Schofield & Horn 1994)
Tangaroa	Jan 1995	Summer	TAN9501	200–800 m		3 303	0.23	(Schofield & Livingston 1995)
Tangaroa	Jan 1996	Summer	TAN9601	200–800 m		2 457	0.13	(Schofield & Livingston 1996)
Tangaroa	Jan 1997	Summer	TAN9701	200–800 m		2 811	0.17	(Schofield & Livingston 1997)
Tangaroa	Jan 1998	Summer	TAN9801	200–800 m		2 873	0.18	(Bagley & Hurst 1998)
Tangaroa	Jan 1999	Summer	TAN9901	200–800 m		2 302	0.12	(Bagley & Livingston 2000)
Tangaroa	Jan 2000	Summer	TAN0001	200–800 m		2 090	0.09	(Stevens et al. 2001)
				200–1000 m		2 152	0.09	(Stevens et al. 2001)
Tangaroa	Jan 2001	Summer	TAN0101	200–800 m		1 589	0.13	(Stevens et al. 2002)
Tangaroa	Jan 2002	Summer	TAN0201	200–800 m		1 567	0.15	(Stevens & Livingston 2003)
				200–1000 m		1 905	0.13	(Stevens & Livingston 2003)
Tangaroa	Jan 2003	Summer	TAN0301	200–800 m		888	0.16	(Livingston et al. 2004)
Tangaroa	Jan 2004	Summer	TAN0401	200–800 m		1 547	0.17	(Livingston & Stevens 2005)
Tangaroa	Jan 2005	Summer	TAN0501	200–800 m		1 048	0.18	(Stevens & O'Driscoll 2006)
Tangaroa	Jan 2006	Summer	TAN0601	200–800 m		1 384	0.19	(Stevens & O'Driscoll 2007)
Tangaroa	Jan 2007	Summer	TAN0701	200–800 m		1 824	0.12	(Stevens et al. 2008)
				200–1000 m		1 976	0.12	(Stevens et al. 2008)
Tangaroa	Jan 2008	Summer	TAN0801	200–800 m		1 257	0.13	(Stevens et al. 2009a)
				200–1000 m		1 323	0.13	(Stevens et al. 2009a)
Tangaroa	Jan 2009	Summer	TAN0901	200–800 m		2 419	0.21	(Stevens et al. 2009b)
Tangaroa	Jan 2010	Summer	TAN1001	200–800 m		1 701	0.25	(Stevens et al. 2011)
				200–1300 m		1 862	0.25	(Stevens et al. 2011)
Tangaroa	Jan 2011	Summer	TAN1101	200–800 m		1 099	0.15	(Stevens et al. 2012)

Vessel	Date	Series	Trip code	Depth	Notes	Biomass	CV	Reference
				200–1300 m		1 201	0.14	(Stevens et al. 2012)
Tangaroa	Jan 2012	Summer	TAN1201	200–800 m		1 292	0.15	(Stevens et al. 2013)
				200–1300 m		1 493	0.13	(Stevens et al. 2013)
Tangaroa	Jan 2013	Summer	TAN1301	200–800 m		1 793	0.15	(Stevens et al. 2014)
				200–1300 m		1 874	0.15	(Stevens et al. 2014)
Tangaroa	Jan 2014	Summer	TAN1401	200–800 m		1 377	0.15	(Stevens et al. 2015)
				200–1300 m		1 510	0.14	(Stevens et al. 2015)
Tangaroa	Jan 2016	Summer	TAN1601	200–800 m		1 299	0.19	(Stevens et al. 2017)
				200–1300 m		1 512	0.16	(Stevens et al. 2017)
Tangaroa	Jan 2018	Summer	TAN1801	200–800 m		1 660	0.34	(Stevens et al. 2018)
				200–1300 m		1 813	0.32	(Stevens et al. 2018)
Tangaroa	Jan 2020	Summer	TAN2001	200–800 m		1 037	0.20	(Stevens et al. 2021)
				200–1300 m		1 126	0.19	(Stevens et al. 2021)
Tangaroa	Jan 2022	Summer	TAN2201	200–800 m		1 651	20.4	(Stevens et al. 2023)
				200–1300 m		1 801	19.0	(Stevens et al. 2023)

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

Table 13: Biomass indices (t) and coefficients of variation (CV) for hake from resource surveys off the west coast South Island. (Estimates assume that the areal availability, vertical availability, and vulnerability are equal to one.)

Vessel	Date	Series	Trip code	Depth	Biomass	CV	Reference
Tangaroa	Jul–Aug 2000	Winter	TAN0007	300–650 m	803	0.13	(O'Driscoll & Ballara 2018)
				200–800 m	–	–	*Not surveyed*
				200–1000 m	–	–	*Not surveyed*
Tangaroa	Jul–Aug 2012	Winter	TAN1210	300–650 m	583	0.13	(O'Driscoll & Ballara 2018)
				200–800 m	1103	0.13	(O'Driscoll & Ballara 2018)
				200–1000 m	–	–	*Not surveyed*
Tangaroa	Jul–Aug 2013	Winter	TAN1308	300–650 m	331	0.17	(O'Driscoll & Ballara 2018)
				200–800 m	747	0.21	(O'Driscoll & Ballara 2018)
				200–1000 m	–	–	*Not surveyed*
Tangaroa	Jul–Aug 2016	Winter	TAN1609	300–650 m	221	0.24	(O'Driscoll & Ballara 2018)
				200–800 m	355	0.16	(O'Driscoll & Ballara 2018)
				200–1000 m	502	0.13	(O'Driscoll & Ballara 2018)
Tangaroa	Jul–Aug 2018	Winter	TAN1807	300–650 m	229	0.33	(O'Driscoll & Ballara 2019)
				200–800 m	559	0.18	(O'Driscoll & Ballara 2019)
				200–1000 m	899	0.14	(O'Driscoll & Ballara 2019)
Tangaroa	Jul–Aug 2021	Winter	TAN2107	300–650 m	507	0.34	(Devine et al. 2022)
				200–800 m	747	0.25	(Devine et al. 2022)
				200–1000 m	939	0.20	(Devine et al. 2022)

Table 14: Biomass indices (t) and coefficients of variation (CV) for hake from inshore resource surveys of Tasman Bay and Golden Bay and the west coast South Island. (Estimates assume that the areal availability, vertical availability, and vulnerability are equal to one.)

Vessel	Date	Series	Trip code	Depth	Biomass	CV	Reference
Kaharoa	Mar–Apr 1992	Autumn	KAH9204	20–400 m	390	0,.25	(MacGibbon 2019)
Kaharoa	Mar–Apr 1994	Autumn	KAH9404	20–400 m	99	0.31	(MacGibbon 2019)
Kaharoa	Mar–Apr 1995	Autumn	KAH9504	20–400 m	5 197	0.27	(MacGibbon 2019)
Kaharoa	Mar–Apr 1997	Autumn	KAH9701	20–400 m	1 019	0..46	(MacGibbon 2019)
Kaharoa	Mar–Apr 2000	Autumn	KAH0004	20–400 m	15	0.36	(MacGibbon 2019)
Kaharoa	Mar–Apr 2003	Autumn	KAH0304	20–400 m	55	0.47	(MacGibbon 2019)
Kaharoa	Mar–Apr 2005	Autumn	KAH0503	20–400 m	1 673	0.30	(MacGibbon 2019)
Kaharoa	Mar–Apr 2007	Autumn	KAH0704	20–400 m	359	0.35	(MacGibbon 2019)
Kaharoa	Mar–Apr 2009	Autumn	KAH0904	20–400 m	212	0.56	(MacGibbon 2019)
Kaharoa	Mar–Apr 2011	Autumn	KAH1104	20–400 m	44	0.36	(MacGibbon 2019)
Kaharoa	Mar–Apr 2013	Autumn	KAH1304	20–400 m	36	0.41	(MacGibbon 2019)
Kaharoa	Mar–Apr 2015	Autumn	KAH1503	20–400 m	81	0.37	(MacGibbon 2019)
Kaharoa	Mar–Apr 2017	Autumn	KAH1703	20–400 m	217	0.61	(MacGibbon 2019)
Kaharoa	Mar–Apr 2019	Autumn	KAH1902	20–400 m	111	0.33	(MacGibbon 2019)
Kaharoa	Mar–Apr 2021	Autumn	KAH2103	20–400 m	179	0.63	(MacGibbon et al. 2022)