Stock Assessment of Southern hake (*Merluccius australis*) in the Falkland Islands

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Summary

Southern hake *Merluccius australis* commercial catches in Falkland Islands licenced fisheries were 3.9 t in 2021; the lowest annual reported total catch since 2015. Following recommendations of the MacAlister Elliott & Partners external review, Total Allowable Catch (TAC) was calculated according to the ICES category 5 advice rule: three-year average catch limited to an 'uncertainty cap' of ± 20% with respect of the TAC set for the current year. The *M. australis* TAC for 2023 is set at 70 t.

Abundance has a declining trend. Annual commercial CPUE reached its lowest level (2.9 kg/h) in 2021. The biomass calculated from the 2022 February surveys was 18% of the biomass calculated from the 2010 February surveys, and the biomass calculated from the 2020 July surveys was 31% of the biomass calculated from the 2017 July surveys.

The length and age analyses suggest that there is no evidence of a detrimental effect of the fishery on size of Southern hake in Falkland Islands waters, with consistent patterns of von Betalannfy L_{Inf}, length at 50% maturity, and modal lengths through time.

Introduction

Southern hake *Merluccius australis* is a predatory benthopelagic species, of which the Patagonian population is found from Chiloé Island in the Pacific, southward around the southern tip of South America to the continental shelf to 59°S, and on the slope north to 38°S in the Atlantic (Froese & Pauly 2022). Post-spawning *M. australis* arrive to the southwest of Falkland Islands waters in austral spring (October–December). In summer (January to March), most individuals are in resting condition and located to the southwest and across the north of the Falkland Islands. In autumn (April to May), *M. australis* occurs more commonly to the west; from May it is found mainly at the western limit of the Falkland Interim Conservation Zone (FICZ) and then migrates to spawning grounds out of Falkland Islands waters (Arkhipkin et al. 2015). Females are larger than males, with maximum sizes in the Falkland Islands fishery at 106 cm total length (TL) for females and 101 cm TL for males. Maximum age has been estimated at 19 years old (Arkhipkin et al. 2015).

Southern hake shares the Falkland Islands zone with the common hake *M. hubbsi* Patagonian stock; both species occur over the shelf and upper continental slope but are spatially separated, with *M. australis* mainly present to the south of 52°S at 150–500 m depth in colder waters, and *M. hubbsi* to the north of 52°S at 100–250 m depth (Lloris et al. 2005; Arkhipkin et al. 2015). Data analyses around Falkland waters have shown that the two hake species can occupy the same feeding grounds by segregating spatially, temporally, and possibly in their diets (Arkhipkin et al. 2003).

Falkland Islands fisheries have reported hake catches since 1987 (Falkland Islands Government 1989); however, Southern hake was not always distinguished from common hake. Southern hake is a more commercially valuable fishery product compared with common hake (Tingley et al. 1995; Arkhipkin et al. 2015) but is taken in much lower quantities, i.e., it represents approximately 0.6% of the total reported hake catch in Falkland Islands fisheries from 2015 to 2021 (Falkland Islands Government *unpublished data*).

Methods

ICES Advice Rules

In 2020, hake was included in the Falkland Islands Government finfish stock assessment and management review conducted by MacAlister Elliott & Partners Ltd, UK (MEP

2020). The MEP report recommended stock assessments for most commercial finfish species to be based on the ICES advice rules (ICES 2012, 2018), referencing applicable categories of data availability and quality. A category 3 assessment framework was recommended for Southern hake (MEP 2020), provided that reliable commercial landings data and abundance indices from surveys are available. Otherwise, a category 5 assessment framework can be implemented.

MEP (2020) also recommended exploring ancillary stock status information from ICES data limited methods such as the Length-Based Indicator method (LBI), which is based on combinations of catch-at-size distributions, and life-history parameters such as L_{Inf} (asymptotic length; Haddon 2001) calculated from length-age data. However, Falkland Islands Southern hake ages have not been validated (Lee et al. 2020; D. Parkyn, FIFD *pers. comm.*), and issues with age data reliability prevent implementation of LBI for Southern hake.

ICES Category 5 Total Allowable Catch

A category 5 assessment framework was implemented given that this category was used for the 2022 TAC calculation (Winter & Ramos 2021). A category 5 assessment framework is based on the average catches from the last 3 years (MEP 2020), limited to an 'uncertainty cap' of ± 20% (ICES 2018) with respect of the TAC set for the current year (TAC_{2022} = 87.74 t; Winter & Ramos 2021):

$$TAC\_5_{2023} = \overline{C_{2019\ to\ 2021}}\ |\ \pm 20\%$$

Commercial catch and CPUE

Catch and CPUE were examined as indices of fishing on this species. Commercial fishing around the Falkland Islands was not distinguished from other parts of the Southwest Atlantic prior to 1982 and catch data by species were recorded systematically from 1987 only (Falkland Islands Government 1989). However, hake catches were not reported at the species level for most of the time series in the Falkland Islands. Subject to this uncertainty, Southern hake catch data were examined from 1987 to 2021 from the Falkland Islands (Falkland Islands

Government[a]; Falkland Islands Government *in prep.*), and Argentina (Argentine Government[b]; Sánchez et al. 2012; Navarro et al. 2014, 2019). Commercial catches and discard of Southern hake were examined by licence type for 2021 in the Falkland Interim Conservation Zone (FICZ).

Catch per unit effort (CPUE) was calculated as the sum of Southern hake catches divided by the sum of effort. Annual CPUE, monthly CPUE through the time series, and the monthly distribution of the CPUE in Falkland Islands waters during 2021 were examined from finfish vessels (A–, G–, and W–licences), which contributed most of the Southern hake catches. Calculations were restricted to the west of the FICZ, where Southern hake predominantly occur (Arkhipkin et al. 2015), defined as the area that includes the 'hake box' (from 60°W to the western limit of the FICZ, and from 51°S to the northern limit of the FICZ), and directly south of the 'hake box' (from 60°W to the western limit of the FICZ, and from 51°S to the southern limit of the FICZ). A preliminary analysis determined that high and constant abundance of Southern hake occurred from January through May; therefore, annual CPUE calculations were also restricted to this range of months. Average monthly CPUE was calculated from 2015 to 2020, and separately for 2021.

Survey biomass estimates

Biomass estimates and the spatial distribution of Southern hake were examined from joint surveys (groundfish and Patagonian squid *Doryteuthis gahi* pre-season surveys) carried out in February 2010, 2011, and 2015 – 2022 in Falkland Islands waters (Ramos & Winter 2022). A trend of the biomass time series from 2010 to 2022 was calculated using LOESS (span = 1, degree = 2). Biomass ratios between the most recent February surveys (2022) and the first February surveys (2010) were estimated as a proxy of the change in biomass over time. Significance of difference and 95% confidence intervals of the change in biomass were computed from the randomized re-samples of the survey biomass estimates (Ramos & Winter 2022).

Biomass estimates, the spatial distribution of Southern hake, and biomass ratios were also examined following Ramos & Winter (2022) from joint surveys (groundfish and

[a] http://www.fig.gov.fk/fisheries/publications/fishery-statistics
[b] https://www.agroindustria.gob.ar/sitio/areas/pesca_maritima/desembarques/

Patagonian squid pre-season surveys) carried out during July 2017 (Gras et al. 2017; Winter et al. 2017) and July 2020 (Randhawa et al. 2020; Winter et al. 2020). The July surveys were conducted for the primary purpose of assessing common hake (Gras et al. 2017; Randhawa et al. 2020), and are presented as an additional comparative proxy for abundance patterns, with the caveat that these would likely reflect variability in the migratory timing of Southern hake.

Length and age analyses

Length-age relationship

The von Bertalanffy growth function (R package 'fishmethods'; Nelson 2019) was used to fit Southern hake length-at-age data available since 1995 in the FIFD database. Growth model parameters (L_{Inf}, k, and t_0) were calculated for females and males using nonlinear least square regression. However, these parameters should be taken with caution given that the quality of Southern hake age data has not been assessed (Lee et al. 2020). Variabilities of the growth model parameters were estimated by bootstrapping; residuals of the model fits were re-sampled randomly with replacement, added back to the expected lengths, and re-fit to the von Bertalanffy growth function. The 95% quantiles of 10,000 iterations were retained as confidence intervals. Inter-annual trends of von Bertalanffy L_{Inf} were calculated by LOESS (span = 1, degree = 2).

Length and age at 50% maturity

Lengths at 50% maturity (L50) were calculated as the mid-point of the binomial logistic regression of maturity ogives vs. length (Heino et al. 2002). Sex and maturity were identified following the fish maturity scale by Brickle et al. (2005; modified from Nikolsky 1963): I) immature; II) resting; III) early developing; IV) late developing; V) ripe; VI) running; VII) spent; VIII) recovering spent. Maturity assignment was simplified to a dichotomous classification of 0) juvenile, including maturity stages I and II, and 1) adult, including maturity stages III to VIII. Southern hake L50 was calculated for females and males separate, from individuals sampled randomly under finfish and experimental (E–licence) vessels across the FICZ from January through May. Southern hake length and maturity data allowed calculating L50 from 2004 to 2021. Years with insufficient immature and mature data, and therefore with logistic models that did not converge, were excluded. Trends of L50 were calculated with LOESS (span = 1, degree = 2). Age at 50% maturity (A50) was calculated for females and males separately, by predicting age corresponding to L50 using the inversed von Bertalanffy equation.

Catch at length

Yearly length frequency distributions, from 2004 to 2021, were examined for females and males to describe patterns in catch at length through time. Unsexed individuals were excluded from the analysis. Lengths of individuals sampled randomly and caught by finfish and experimental vessels across the FICZ from January through May (the months with higher presence of Southern hake in the area) were included in the analysis. Yearly length frequencies were compared with yearly L50 to assess if the catch is mainly comprised of immature or mature individuals.

Catch at age

Age data were used to create an age-length key, from which ages were assigned to length data (R package 'FSA'; Ogle et al. 2022) of individuals sampled randomly in the FICZ from 2005 to 2021. Catch at age proportions were examined as a proxy for fishing pressure at each age class per year. Relative frequencies of immature vs mature age classes (corresponding to lesser vs greater than L50) in the catch were assessed for females and males separately through time. Older age classes with negligible representation in the catch were excluded.

Natural mortality

Natural mortality (M) was calculated as an indicator to examine vulnerability of the stock. Natural mortality is the component of total mortality that is not caused by fishing, but by causes such as predation, diseases, senility, pollution, amongst other factors. Annual natural mortality refers to the proportion of fish dying during the year expressed as a fraction of the fish alive at the beginning of the year (FAO 1999), and was calculated using equation 1 following Then et al. (2015):

$$\mathrm{M} = 4.899 \times \mathrm{t}_{\mathrm{max}}^{-0.916} \qquad \text{Eqn. 1}$$

where t_{max} = maximum age, taken as the oldest age reported in the FIFD database not considered an outlier. Then et al. (2015) recommended the use of the t_{max}-based estimator over other estimators based on cross-validation of prediction error, model residual patterns, model parsimony, and biological considerations.

All analyses were performed in RStudio (R Core Team 2021).

Results

ICES Advice Rules

ICES Category 5 Total Allowable Catch

ICES category 5 TAC for next year calculated as the average of the in-zone catch (t) of the last completed three years (49.27 t):

$$TAC\_5_{2023} = \overline{95.69 + 48.24 + 3.89} = 49.27$$

limited to a 20% cap reduction with respect of the TAC for the current year (TAC_{2022} = 87.74 t; Winter & Ramos 2021) resulted in a TAC for 2023 of 70.19 t:

$$TAC\_5_{2023} = TAC_{2022} \mid -20\% = 87.74 \mid -17.55 = 70.19$$

Note that the year jumps from 2021 to 2023. Standard procedure is to inform next year's allowable catch with data up to the last completed year, i.e., the previous year (2021), as licencing advice must be issued while the current year is still in progress.

Commercial catch and CPUE

Southern hake catches in Falkland Islands waters have been on average 133 t per year since 2015, representing approximately 12% of the Falkland Islands and Argentine combined annual catch (Fig. 1; Appendix I).

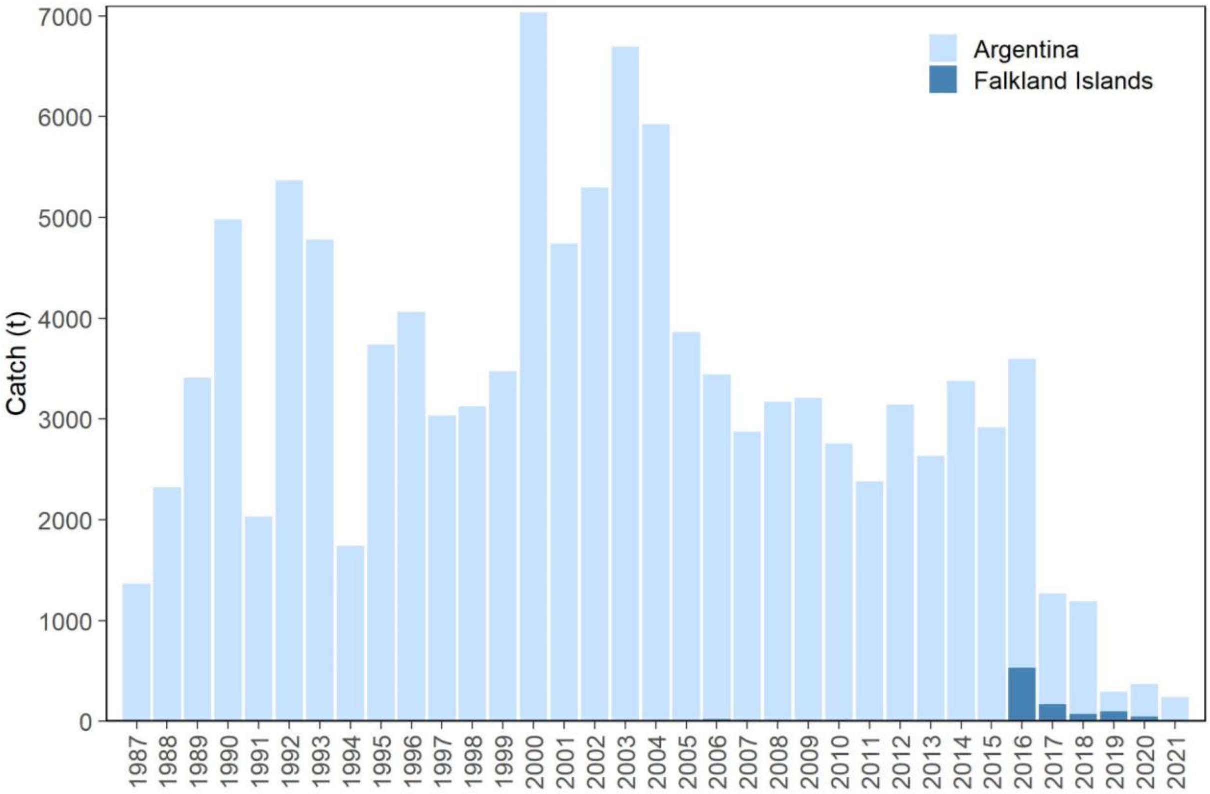


Fig. 1. Annual commercial catch of Southern hake in Falkland Islands and Argentine waters. Falkland Islands commercial catch data exclude experimental (E–licence) and out-of-zone (O–licence) licences from 1990; earlier than 1990 these licences were not designated.

During 2021, a total of 4.3 t of Southern hake were reported caught in Falkland Islands waters, of which 3.9 t was reported under commercial licences, i.e., excluding the experimental E–licence. Finfish G–, and W–licences accounted for 6% and 84% of the total Southern hake catch, respectively. Southern hake discards were 20% of the total Southern hake catch in 2021; finfish licences discarded 11%, and experimental (E–) and calamari (C–, and X–) licences discarded the entire Southern hake catch (Table I).

Table I. Catch proportion of Southern hake by licence type in Falkland Islands waters during 2021.

Licence	Target species	Catch (t)	Catch (%)	Discard (t)	Proportion discarded (%)
W	Restricted finfish	3.615	84.09	0.348	9.63
E	Experimental	0.405	9.42	0.405	100.00
G	Restricted finfish and *Illex*	0.255	5.93	0.084	32.94
X	Calamari 2nd season	0.019	0.44	0.019	100.00
C	Calamari 1st season	0.005	0.12	0.005	100.00
A	Unrestricted finfish	0.000	0.00	0.000	0.00
B	*Illex* squid	0.000	0.00	0.000	0.00
F[a]	Skates and rays	0.000	0.00	0.000	0.00
L	Toothfish (longline)	0.000	0.00	0.000	0.00
O	Outside Falkland Islands waters	0.000	0.00	0.000	0.00
S[a]	Southern blue whiting and hoki	0.000	0.00	0.000	0.00
Total		4.299	100	0.861	20.03

[a] F and S licenses were not fished during 2021.

CPUE by finfish vessels to the west of the Falkland Islands from January through May had a statistically significant declining trend from 2016 (66.3 kg/h) to 2021 (2.9 kg/h) (Fig. 2).

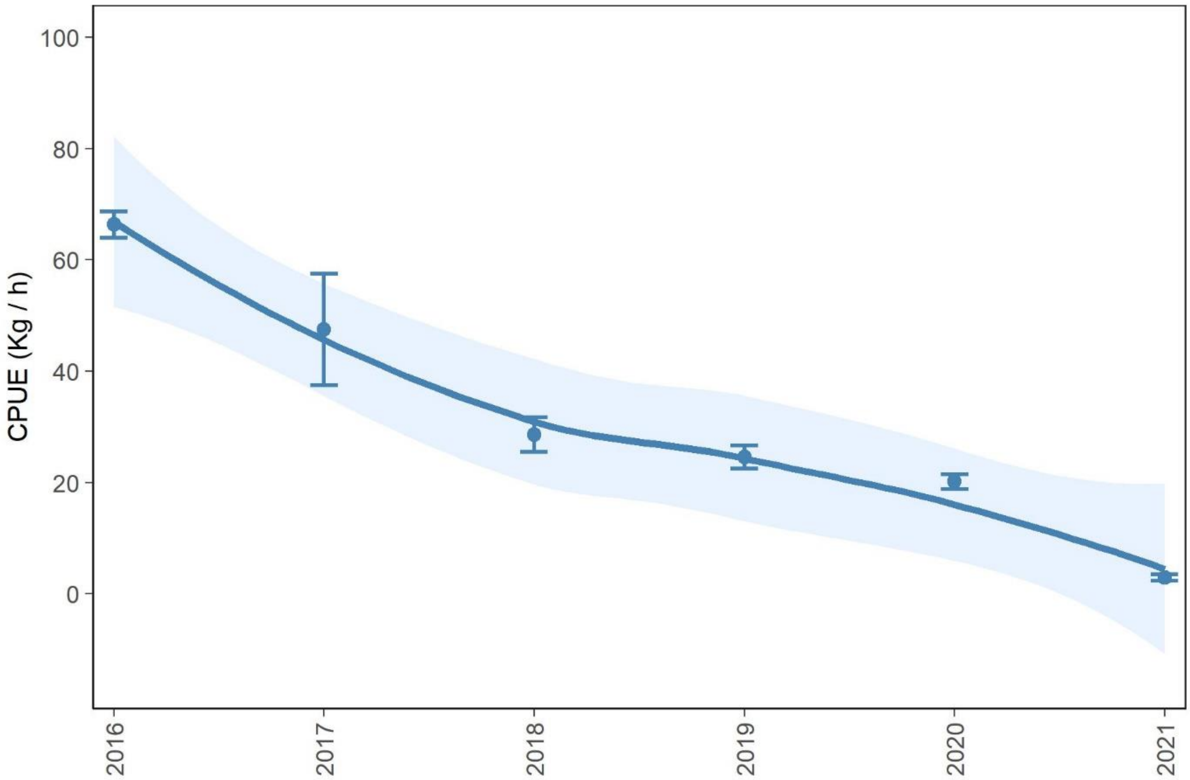


Fig. 2. Yearly CPUE ± 1 standard error of Southern hake in Falkland Islands waters from 2016 through 2021, calculated from finfish (A–, G–, and W–licences) vessels from the west of 60°W in the FICZ (hake box and south of hake box), from January through May, with LOESS smooth ± 95% confidence intervals (LOESS; span = 1, degree = 2).

Monthly CPUE by finfish vessels were examined separately from 2015 to 2020 to compare the overall trend through time with the 2021 (previous year) trend. Monthly CPUE by finfish vessels to the west of the Falkland Islands from 2015 to 2020 ranged from 6 kg/h in September to 73 kg/h in March. CPUE was higher from January through May, declined over the following months and increased again towards the end of the year (Fig. 3). This pattern suggests that Southern hake is more abundant in Falkland Islands waters from summer to mid-autumn. In 2021, there was no fishing effort during January and February, and effort was higher in October and December; higher CPUE therefore was reported towards the end of the year, with December having the highest CPUE (34 kg/h; Fig. 3; Appendix II). During 2021, Southern hake were caught mainly to the southwest of West Falkland under finfish licences (Appendix III).

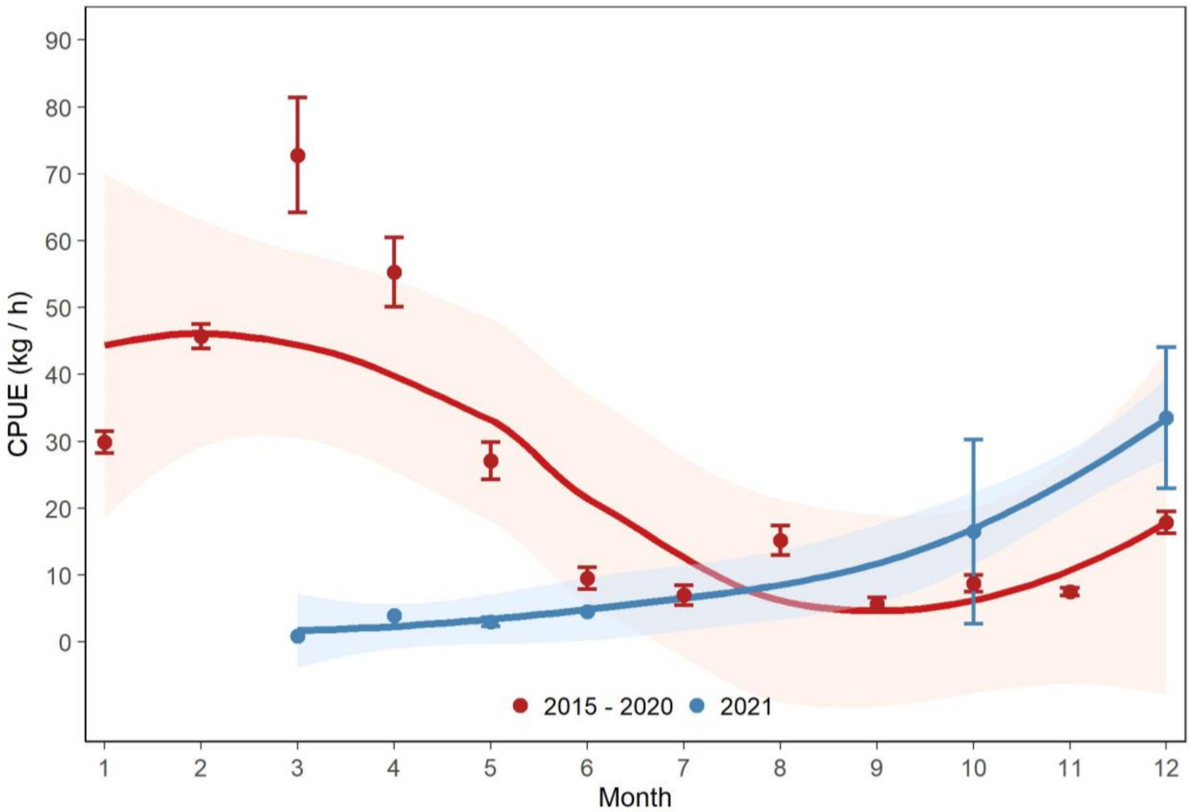


Fig. 3. Monthly CPUE ± 1 standard error of Southern hake in Falkland Islands waters for 2015–2020 (red), and 2021 (blue), calculated from finfish (A–, G–, and W–licences) vessels, with LOESS smooths ± 95% confidence intervals (LOESS; span = 1, degree = 2).

Surveys biomass estimates
Summer surveys (February)

The biomass of Southern hake during the February surveys had a statistically significant decreasing trend from 2010 to 2022, although with high variability in biomass calculations in some years, and with the lowest biomass in the time series calculated for 2019. The biomass in 2022 (920 t) was 18% of the biomass in 2010 (5,097 t; Fig. 4; Appendix IV). All 10,000 out of 10,000 paired re-samples had lower biomass estimate values in February 2022 than in February 2010 (100%), therefore the difference in biomass between 2022 and 2010 is significant at $p < 0.05$. During the February surveys, Southern hake was distributed to the southwest of the FICZ and the main aggregations occurred to the limit of the FICZ (Appendix V).

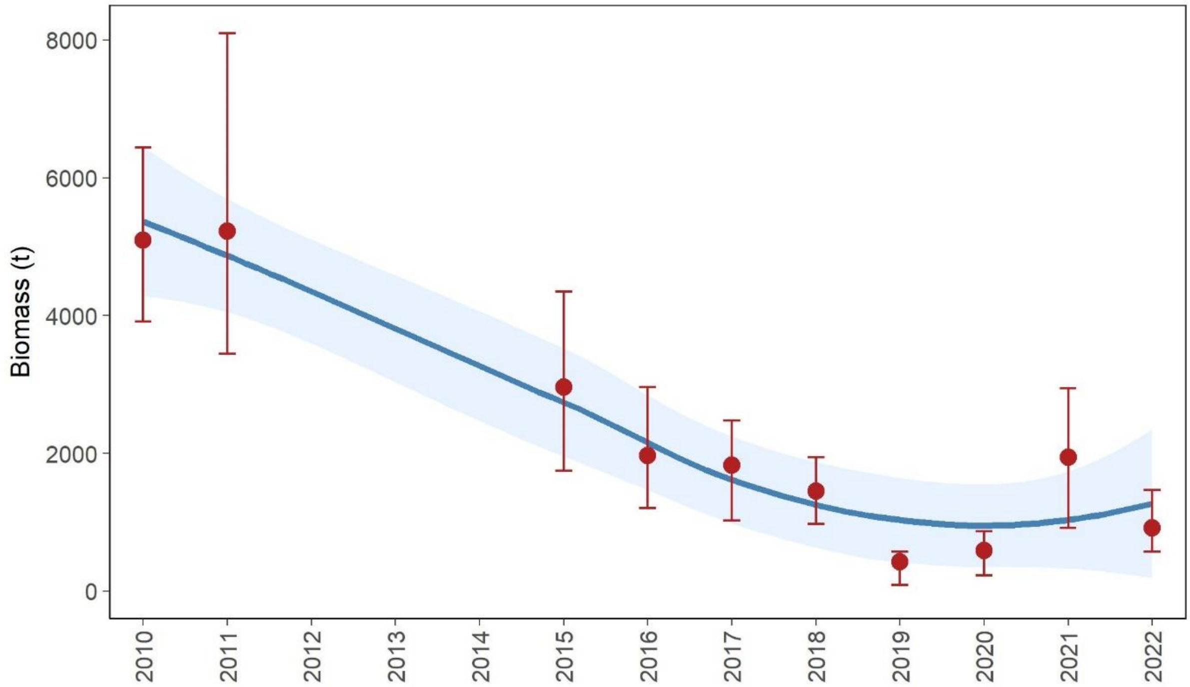


Fig. 4. Southern hake biomass estimates (red dots) ± 95% confidence intervals from February surveys in Falkland Islands waters, with LOESS smooths ± 95% confidence intervals (LOESS; span = 1, degree = 2). No parallel February surveys (groundfish and Patagonian squid pre-season surveys) were conducted in 2012, 2013, and 2014.

Winter surveys (July)

The calculated biomass of Southern hake in the July 2020 survey (171 t) was 31% of the July 2017 survey (506 t; Table II). A total of 9,554 out of 10,000 paired re-samples had higher biomass estimate values in July 2017 than in July 2020 (95.5%), thus significant at p <

0.05. During the July surveys, Southern hake was distributed to the southwest of the FICZ, with the main aggregations near the southwest limit (Appendix VI).

Table II. Winter (July) surveys catch and effort, and biomass estimates (mean ± 95% confidence intervals) of Southern hake in Falkland Islands waters.

Year	Survey	Trawls (n)	Swept area (km^2)	Effort (h)	Catch (kg)	CPUE (kg/h)	Biomass (t)
2017	Groundfish	74	15.41	74	43.43	0.59	506.11 (216.40 – 717.41)
	D. gahi[a]	59	54.71	114	17.67	0.16	
	Total	133	70.12	188	61.10	0.32	
2020	Groundfish[b]	33	7.14	33	12.12	0.37	170.70 (0.89 – 412.27)
	D. gahi	55	98.57	101	9.10	0.09	
	Total	88	105.71	134	21.22	0.16	

[a]An additional one-day transect of four trawls was taken in shallow inshore waters to sample for juvenile toothfish. These four trawls were not included in analyses as their locations were not relevant to the distribution of Southern hake.
[b]Twelve additional trawls were conducted in high seas during the July 2020 survey; these trawls were not included in the analyses.
Note that no parallel July surveys (groundfish and Patagonian squid pre-season surveys) were conducted in 2018 and 2019.

Length and age analyses

Length-age relationship

The length-age relationship of females and males pooled (n = 3,810) gave the values: L_{Inf} = 93.29 cm, k = 0.1720, and t_0 = -1.3719 years. Length and age of females (n = 3,210) ranged from 35 cm to 107 cm, and from 2 year to 21 years, respectively. The length-age relationship of females gave the values: L_{Inf} = 95.78 cm, k = 0.1587, and t_0 = -1.6699 years. Length and age of males (n = 600) ranged from 31 cm to 110 cm and from 2 years to 17 years, respectively. The length-age relationship of males gave the values: L_{Inf} = 81.97 cm, k = 0.2497, and t_0 = -0.3442 years (Appendix VII).

Female and male asymptotic lengths (L_{Inf}) did not change significantly from 2002 to 2018 (Fig. 5). However, Southern hake age data was limited, which is reflected in data gaps in several years before 2018, and from 2019 onwards for both females and males. Limited age data may have also resulted in wide confidence intervals for most years when it was possible to calculate L_{Inf} (Appendix VIII).

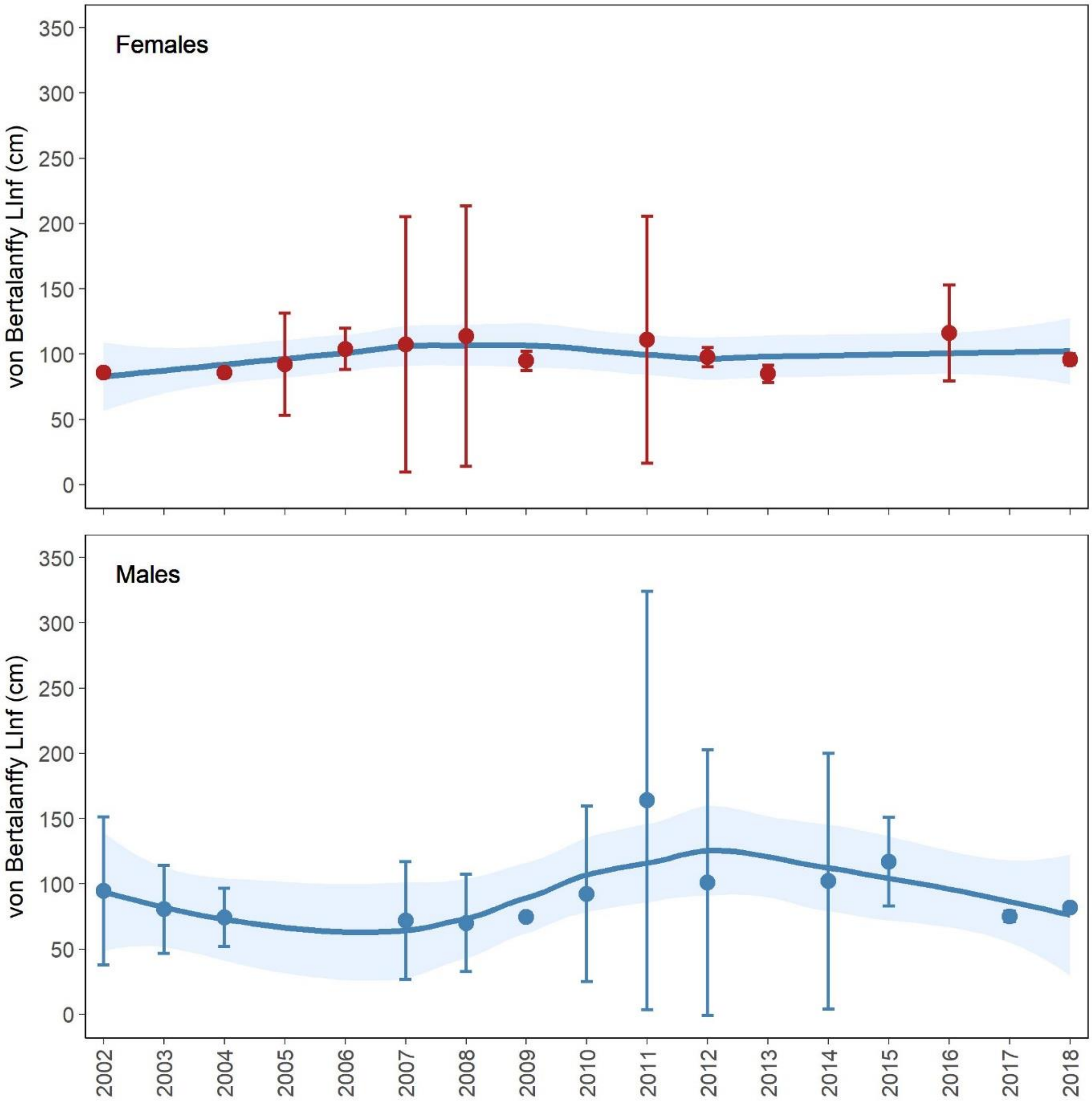


Fig. 5. Asymptotic lengths (L_{Inf}) ± 1 standard error calculated according to the von Bertalanffy growth function for female (red dots) and male (blue dots) Southern hake from 2002 to 2018, with LOESS smooths ± 95% confidence intervals (LOESS; span = 1, degree = 2). Note the gap in some years when data were limited.

Length and age at 50% maturity

Over the entire time series, length at 50% maturity (L50) of females was 72.63 ± 0.40 cm total length (n = 3,743) and age at 50% maturity (A50) was 7.2 years old. L50 of males was 63.09 ± 0.70 cm total length (n = 578) and A50 was at 5.5 years old. Therefore, immature females are inferred as < 8 years old and mature females are inferred as ≥ 8 years old, and immature males are inferred as < 6 years old and mature males are inferred as ≥ 6 years old. Annual L50 and A50 of females ranged from 58 cm and 4.3 years in 2009 to 77 cm and 8.4

years in 2004. Annual L50 and A50 of males ranged from 35 cm and 2.4 years in 2011 to 75 cm and 8.3 years in 2007. The L50 fit did not change significantly for females and males since 2004 (Fig. 6; Appendixes IX–X).

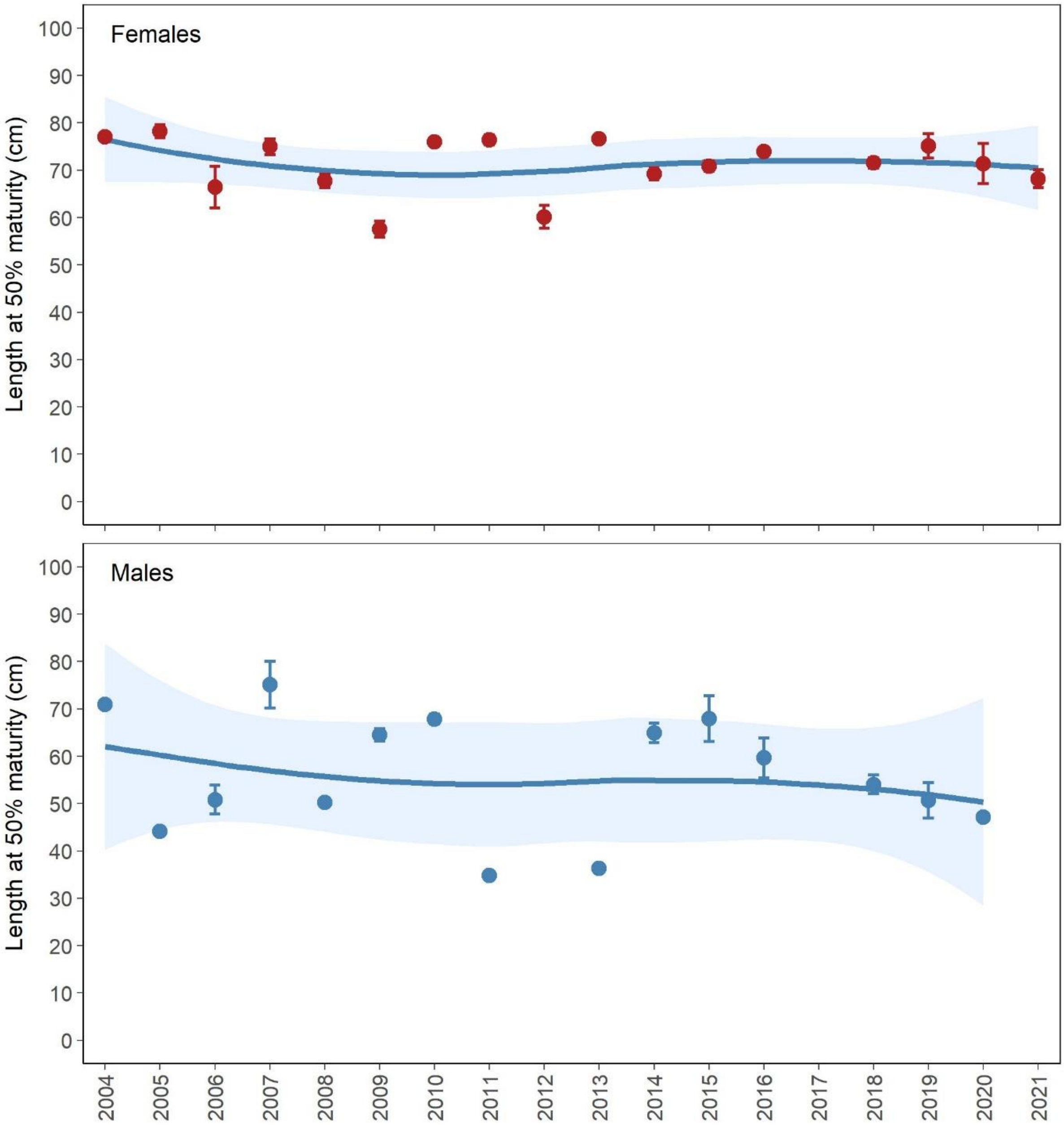


Fig. 6. Lengths at 50% maturity (L50) ± 1 standard error of female (red dots) and male (blue dots) Southern hake caught in Falkland Islands waters from January through May, from 2004 through 2021, with LOESS smooths ± 95% confidence intervals (LOESS; span = 1, degree = 2).

Catch at length

Female Southern hake (n = 3,923) ranged from 27 cm to 107 cm total length, and males (n = 667) ranged from 31 cm to 98 cm total length. Females were mostly caught at sizes smaller than L50 (Fig. 7); however, the little number of individuals per year limits our capacity to compare length frequencies vs L50, in particular for males (Fig. 7; Appendix XI).

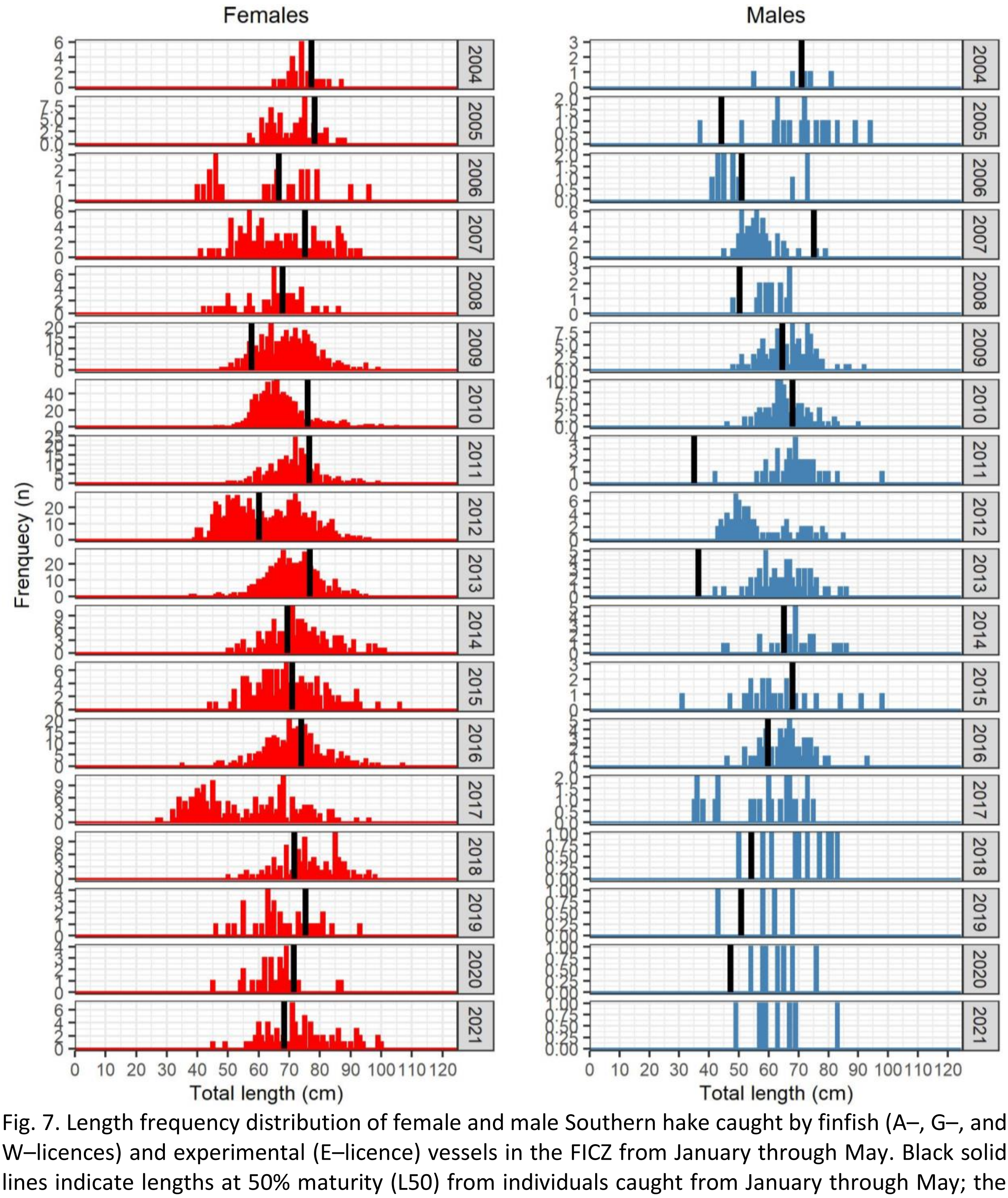


Fig. 7. Length frequency distribution of female and male Southern hake caught by finfish (A–, G–, and W–licences) and experimental (E–licence) vessels in the FICZ from January through May. Black solid lines indicate lengths at 50% maturity (L50) from individuals caught from January through May; the binomial model for L50 did not fit the female data in 2017, and the male data in 2012, 2017, and 2021.

Catch at age

Greater proportions of female and male Southern hake were consistently caught at sizes equivalent to ages < 8 years old than at sizes equivalent to ages ≥ 8 years old through the time series (Appendixes XII–XIII). The proportion of immature (ages 1 to 7) and mature (ages 8 to 15) females, and immature (ages 1 to 5) and mature (ages 6 to 15) males in the annual catch did not appear to vary from 2004 to 2021 (Fig. 8).

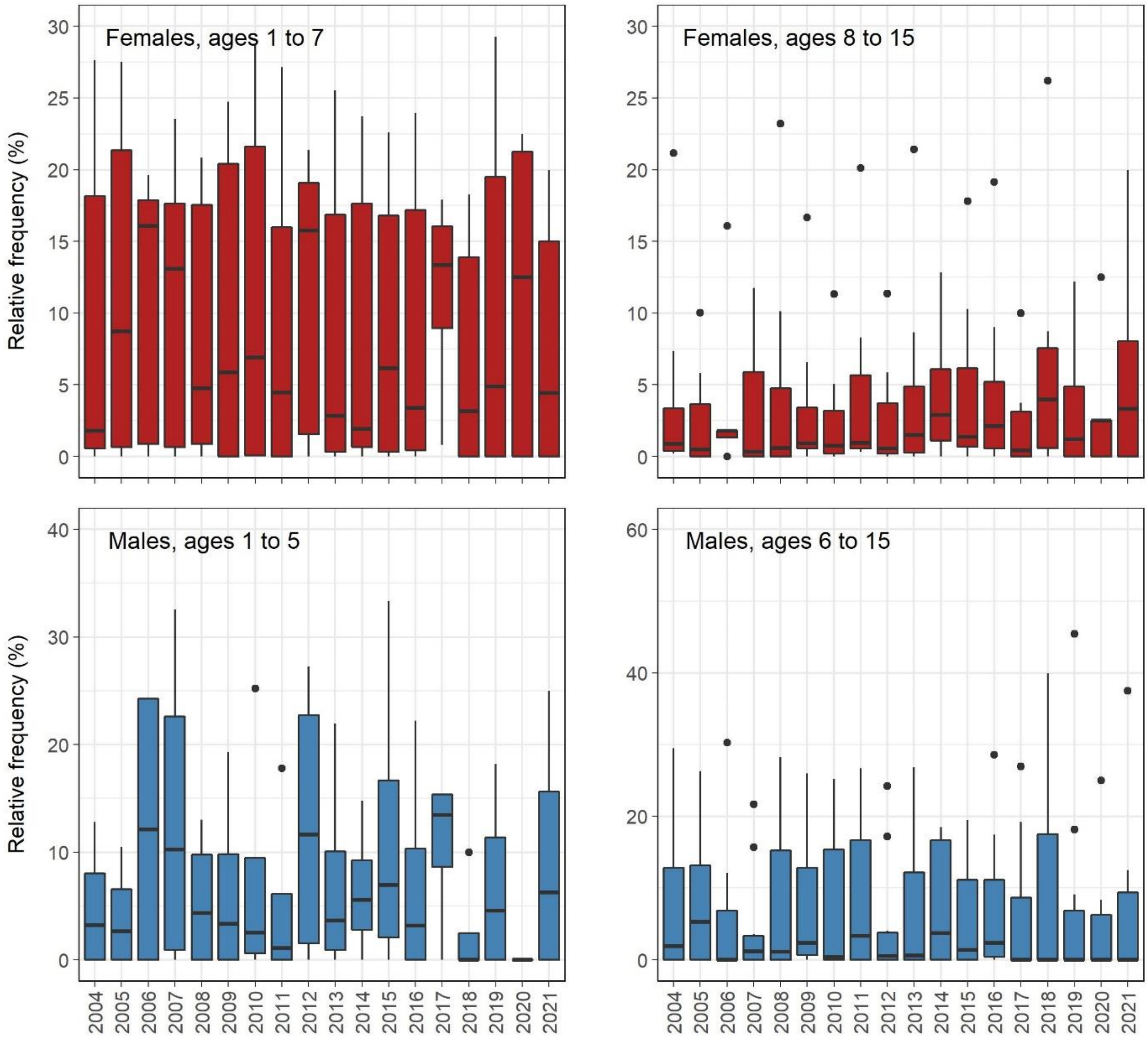


Fig. 8. Catch at age of immature (Females: ages 1 to 7; Males: ages 1 to 5; left panel) and mature (Females: ages 8 to 15; Males: ages 6 to 15; right panel) Southern hake caught by finfish (A–, G–, and W–licences) and experimental (E–licence) vessels in the FICZ from 2004 to 2021. Southern hake ages > 15 were sparse and are not included on the figure.

Natural mortality

Equation 1 resulted in a natural mortality (M) calculation of:

$$M = 4.899 \times t_{max}^{-0.916} = 4.899 \times 21^{-0.916} = 0.3013$$

indicating that 30% of the stock dies per year not by fishing but due to natural causes such as predation, diseases, senility, amongst others.

Conclusions

Southern hake Total Allowable Catch for 2023 was set at 70 t, calculated using the ICES category 5 framework weighted by inverse variance of February surveys biomass estimates and with 20% cap. This stock must be monitored carefully for various reasons:

1) The abundance of Southern hake in Falkland Islands waters has decreased since 2010, as indicated by declining trends in February surveys and in July surveys biomasses, as well as by the declining trend of commercial CPUE. The decline in abundance of this stock may be associated with changes in its migratory pattern driven by changing oceanographic conditions, or by high fishing pressure beyond the FICZ; further studies may clarify the observed trends in abundance.

2) Southern hake was aged mainly at MFRI in Gdynia. As the FIFD has not assessed the reliability of Southern hake age estimates, these should be taken with caution given the status of 'uncertainty' for most finfish species aged at MFRI (Lee et al. 2020). Some years lacked age data; therefore, efforts must be made towards producing and verifying more age data to implement robust analyses, to be able to provide appropriate advice for management.

The length and age analyses show no evidence of a detrimental effect of the fishery on size of Southern hake in Falkland Islands waters, with patterns of von Bertalanffy L_{Inf}, length at 50% maturity, and modal lengths that have not changed significantly through time for females and males. However, the limited biological data and the uncertainty of age data of this species must be taken in consideration; the interpretation of these patterns should therefore be cautious. Comparison of length and age at 50% maturity and catch at length and age revealed that Southern hake are mainly caught before reaching maturity, which can reduce stock sustainability (Vasilakopoulos et al. 2011; Muluye et al. 2016; Ben-Hasan et al. 2021). Finally, natural mortality of Southern hake in the FICZ was moderate (M = 0.3013); improvements to age data will allow estimating fishing mortality, to be able to assess total mortality (natural mortality + fishing mortality) on this stock.

References

Arkhipkin AI, Laptikhovsky VV, Barton AJ (2015) Biology and fishery of common hake (*Merluccius hubbsi*) and southern hake (*Merluccius australis*) around the Falkland/Malvinas Islands on the Patagonian shelf of the Southwest Atlantic Ocean. In: Arancibia H (Ed.) Hakes, Biology and Exploitation, pp. 154-184. Oxford: Wiley.

Arkhipkin AI, Middleton DAJ, Portela JM, Bellido JM (2003) Alternative usage of common feeding grounds by large predators: the case of two hakes (*Merluccius hubbsi* and *M. australis*) in the southwest Atlantic. Aquatic Living Resources 16: 487-500.

Ben-Hasan A, Walters C, Hordyk A, Christensen V (2021) Alleviating Growth and Recruitment Overfishing through Simple Management Changes: Insights from an Overexploited Long-Lived Fish. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 13, 87–98. https://doi.org/10.1002/mcf2.10140

Brickle P, Laptikhovsky V, Arkhipkin A (2005) Reproductive strategy of a primitive temperate notothenioid *Eleginops maclovinus*. Journal of Fish Biology 66, 1044–1059. https://doi.org/10.1111/j.1095-8649.2005.00663.x

FAO (1999) FAO Fisheries Technical Paper. No. 382. Rome, FAO. 113 p.

Falkland Islands Government (1989) Falkland Islands Interim Conservation & Management Zone Fisheries Report '87/88. Fisheries Department, Port Stanley, Falkland Islands. 45 p.

Falkland Islands Government (2022) Fisheries Department Fisheries Statistics, Volume 26. Stanley, Falkland Islands. 68 p.

Froese R, Pauly D (Eds.) (2022) FishBase. World Wide Web electronic publication. www.fishbase.org

Gras M, Pompert J, Blake A, Busbridge T, Boag T, Huillier JT, Concha F (2017) Report of the 2017 ground fish survey ZDLT1–07–2017. Technical Document, FIG Fisheries Department. 68 p.

Haddon M (2001) Modelling and quantitative methods in fisheries. Chapman & Hall/CRC, Boca Raton, Florida. 406 pp.

Heino M, Dieckmann U, Godø OR (2002) Measuring probabilistic reaction norms for age and size at maturation. Evolution 56: 669–678.

ICES (2012) ICES Implementation of Advice for Data limited Stocks in its 2012 Advice. http://www.ices.dk/sites/pub/Publication%20Reports/Expert%20Group%20Report/acom/2012/ADHOC/DLS%20Guidance%20Report%202012.pdf

ICES (2018) General context of ICES advice. https://www.ices.dk/sites/pub/Publication%20Reports/Advice/2018/2018/Introduction_to_advice_2018.pdf

Lee B, Shcherbich Z, Randhawa H (2020) Towards the development of an ageing strategy for finfish in the Falkland Islands trawl fisheries. Technical Document, FIG Fisheries Department. 23 p.

Lloris D, Matallanas J, Oliver P (2005) Hakes of the world (Family Merlucciidae). An annotated and illustrated catalogue of hake species known to date. FAO Species Catalogue for Fishery Purposes. No. 2. Rome, FAO. 57p.

MEP (2020) Annex 3: Review of Finfish Stock Assessments. Report for Falkland Islands Government. MacAlister Elliot & Partners Ltd. 47 p.

Muluye T, Tekle-Giorgis Y, Tilahun G (2016) The Extent of Immature Fish Harvesting by the Commercial Fishery in Lake Hawassa, Ethiopia. Momona Ethiopian Journal of Science 8, 37–49. https://doi.org/10.4314/mejs.v8i1.3

Navarro G, Rozycki V, Monsalvo M (2014) Estadísticas de la pesca marina en la Argentina. Evolución de los desembarques 2008-2013. Ministerio de Agricultura, Ganaderia y Pesca de la Nación. Buenos Aires, 144 p.

Navarro G, Rozycki V, Monsalvo M (2019) Estadísticas de la pesca marina en Argentina. Evolución de los desembarques 2012-2016. Secretaria de Gobierno de Agroindustria, 147 p.

Nelson GA (2019) Package 'fishmethods': Fishery science methods and models from published literature and contributions from colleagues. R package version 1.11-1.

Nikolsky GV (1963) *The Ecology of Fishes*. New York, USA: Adademic Press. In: Brickle P, Laptikhovsky V, Arkhipkin A (2005) Reproductive strategy of a primitive temperate notothenioid *Eleginops maclovinus*. Journal of Fish Biology 66, 1044–1059. https://doi.org/10.1111/j.1095-8649.2005.00663.x

Ramos JE, Winter A (2022) February bottom trawl survey biomasses of fishery species in Falkland Islands waters, 2010–2022. SA–2022–05. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, Stanley, Falkland Islands. 86 pp.

Randhawa HS, Blake A, Trevizan T, Brewin J, Evans D, Kairua T, Büring T (2020) Cruise Report ZDLT1-07-2020: 2020 Hake Demography Survey. Technical Document, FIG Fisheries Department. 135 p.

R Core Team (2021) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Sánchez R, Navarro G, Rozycki V (2012) Estadísticas de la pesca marina en la Argentina. Evolución de los desembarques 1898-2010. Ministerio de Agricultura, Ganaderia y Pesca de la Nación. Buenos Aires, 528 p.

Then AY, Hoenig JM, Hall NG, Hewitt DA (2015) Evaluating the predictive performance of empirical estimators of natural mortality rate using information on over 200 fish species. ICES Journal of Marine Science 72:82–92. https://doi.org/10.1093/icesjms/fsu136

Tingley GA, Purchase LV, Bravington MV, Holden SJ (1995) Biology and fisheries of hakes (*M. hubbsi and M. australis*) around the Falkland Islands. In: Alheit J, Pitcher TJ (Eds.) Hake: Biology, fisheries and markets, pp. 269–303. Chapman & Hall Fish and Fisheries Series, vol. 15. Springer, Dordrecht.

Vasilakopoulos P, O'Neill FG, Marshall CT (2021) Misspent youth: does catching immature fish affect fisheries sustainability? ICES Journal of Marine Science 68, 1525–1534. https://doi.org/10.1093/icesjms/fsr075

Winter A, Ramos JE (2021) Stock assessment of southern hake (*Merluccius australis*) in the Falkland Islands. SA–2021–PAT. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, Stanley, Falkland Islands. 13 p.

Winter A, Ramos JE, Shcherbich Z, Tutjavi V, Matošević N (2020) Falkland calamari (*Doryteuthis gahi*) stock assessment survey, 2nd season 2020. Technical Document, FIG Fisheries Department. 17 p.

Winter A, Shcherbich Z, Iriarte V, Derbyshire C (2017) *Doryteuthis gahi* stock assessment survey, 2nd season 2017. Technical Document, FIG Fisheries Department. 25 p.

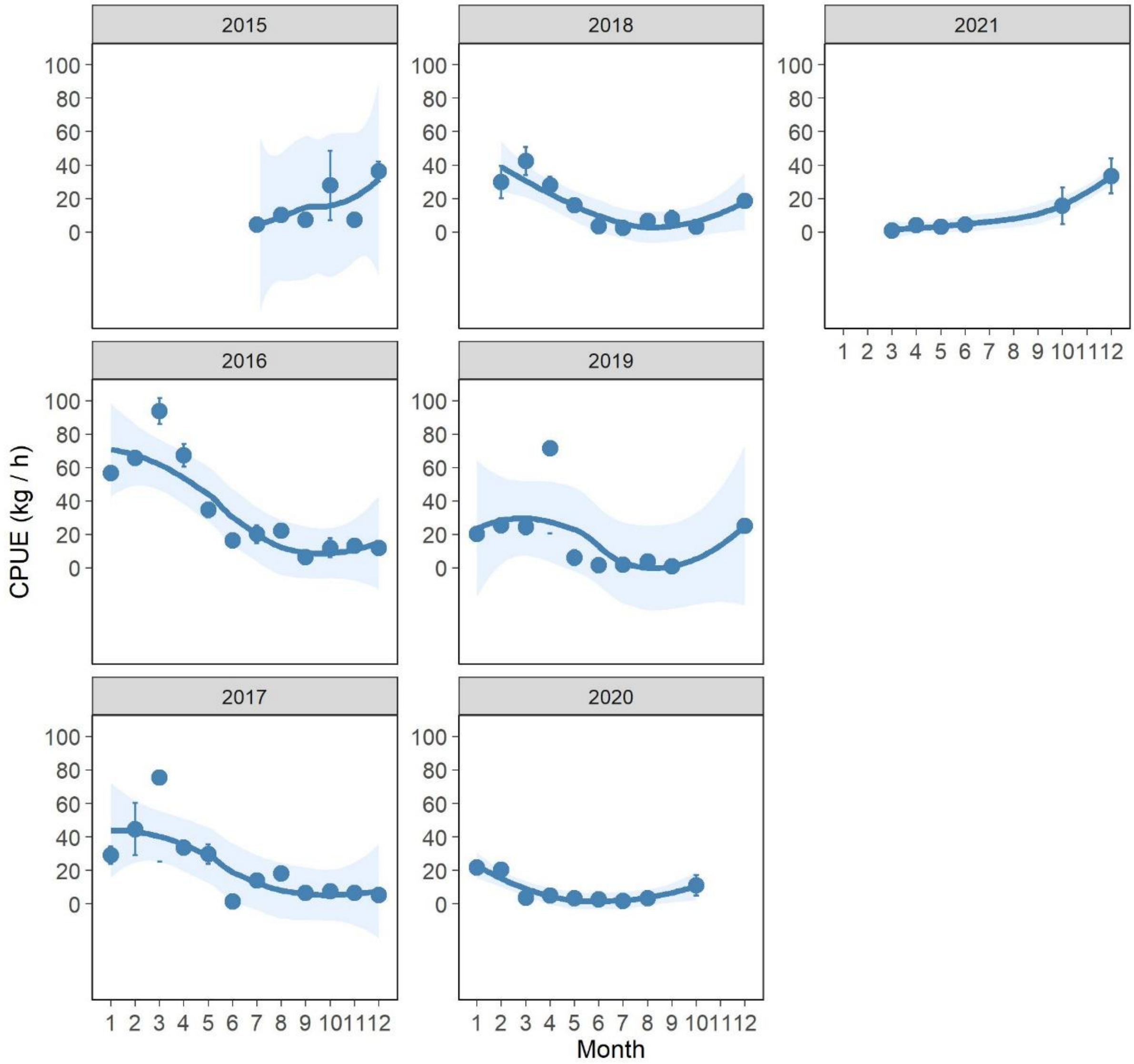
Appendix

Appendix I. Annual commercial catches (t) of Southern hake reported in Falkland Islands (excluding E–licence from 1987 through 2021; Falkland Islands Government 2022.[c]) and Argentina (Argentine Government[d]; Sánchez et al. 2012; Navarro et al. 2014, 2019).

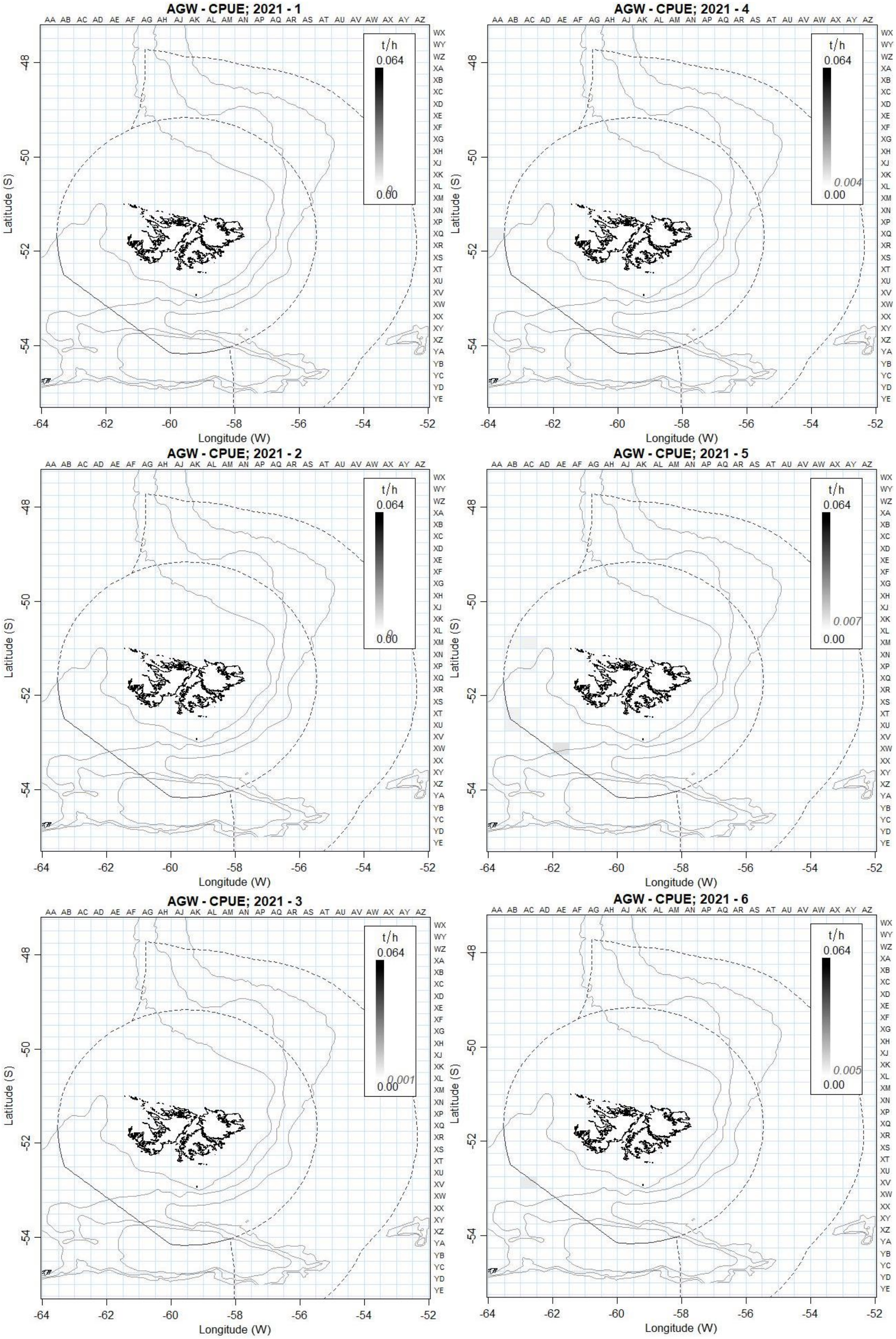
Year	Falkland Islands (t)	Argentina (t)
1987	NA	1,364.00
1988	NA	2,326.00
1989	NA	3,412.90
1990	NA	4,983.70
1991	NA	2,032.00
1992	NA	5,368.30
1993	NA	4,781.80
1994	NA	1,742.50
1995	NA	3,740.70
1996	NA	4,062.80
1997	NA	3,036.70
1998	NA	3,126.30
1999	NA	3,471.80
2000	NA	7,034.80
2001	NA	4,742.20
2002	NA	5,300.80
2003	NA	6,692.80
2004	NA	5,922.70
2005	0.50	3,865.30
2006	23.30	3,418.20
2007	NA	2,870.60
2008	NA	3,171.50
2009	NA	3,211.70
2010	NA	2,754.60
2011	NA	2,383.20
2012	NA	3,142.92
2013	0.00	2,632.85
2014	NA	3,376.28
2015	13.53	2,907.44
2016	530.97	3,066.17
2017	169.97	1,097.11
2018	70.41	1,125.09
2019	95.69	197.45
2020	48.24	324.81
2021	3.89	239.20

[c] http://www.fig.gov.fk/fisheries/publications/fishery-statistics
[d] https://www.agroindustria.gob.ar/sitio/areas/pesca_maritima/desembarques/

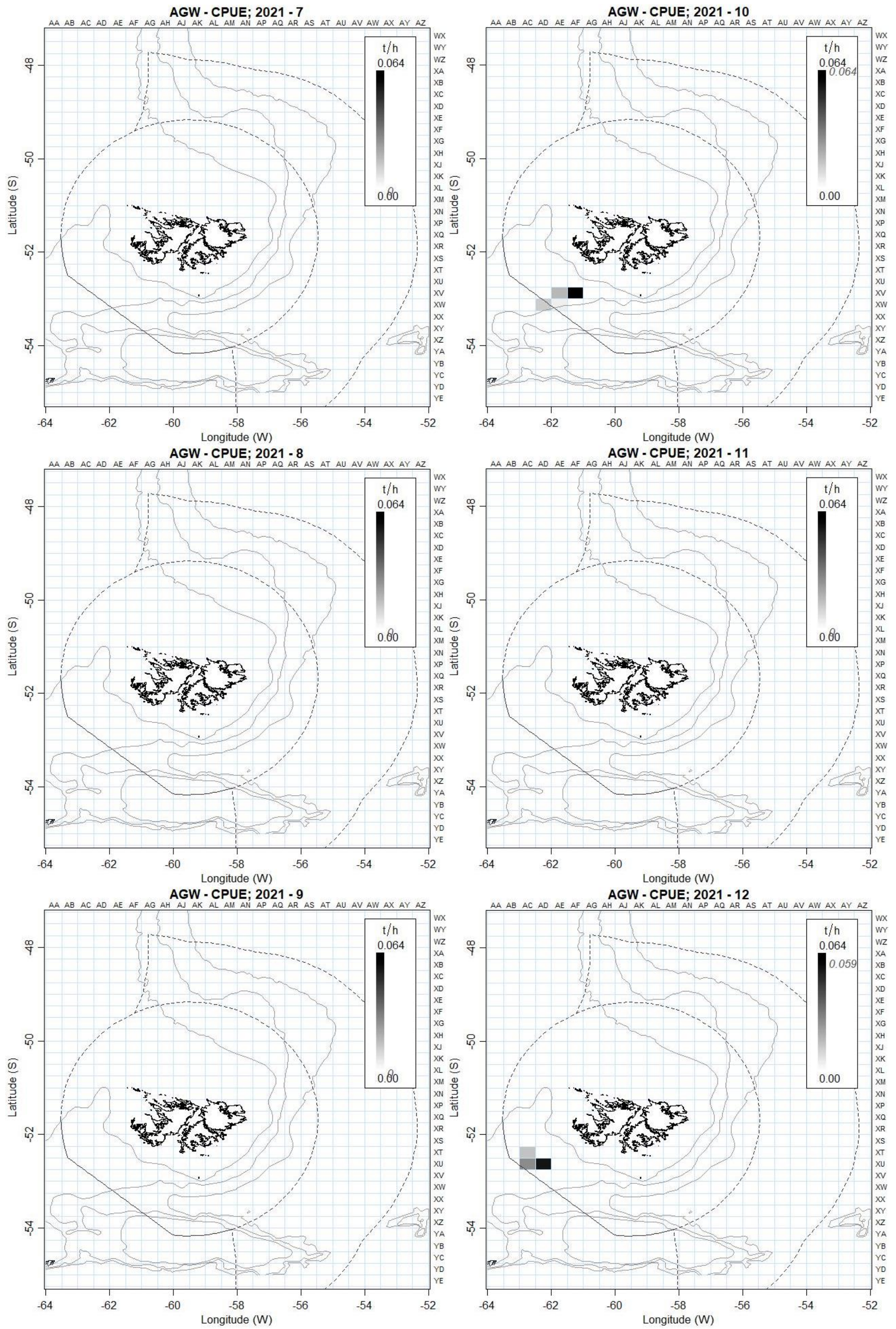
Appendix II. Monthly CPUE of Southern hake in Falkland Islands waters from 2015 to 2021, calculated from finfish (A–, G–, and W–licences) vessels, with LOESS smooths ± 95% confidence intervals.



Appendix III. Monthly CPUE of Southern hake in Falkland Islands waters during 2021, estimated from finfish (A–, G–, and W–licences) vessels. There was no fishing effort during January and February under finfish licences.



Appendix III. *continued…*

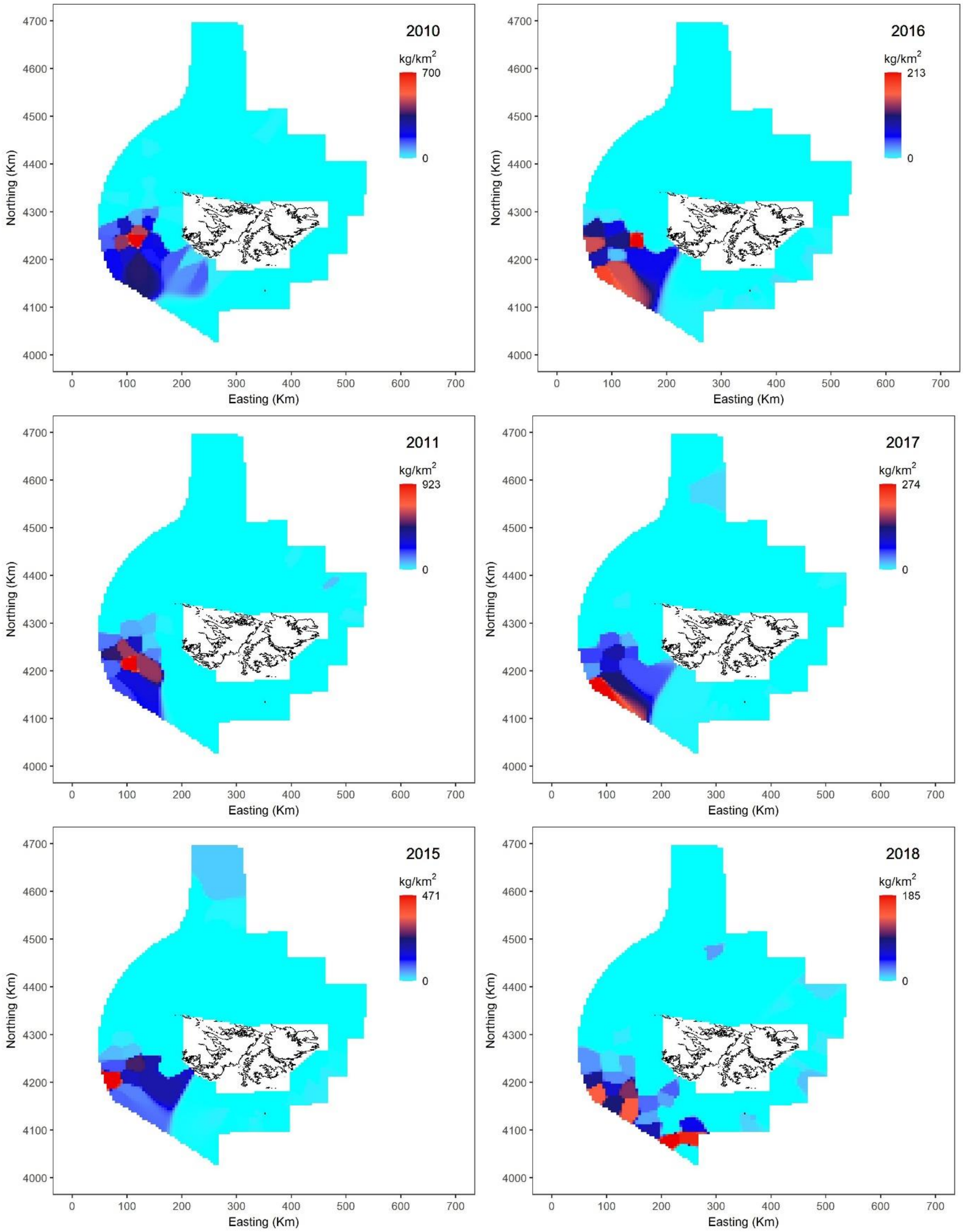


Appendix IV. Summer (February) surveys catch and effort, and biomass estimates (mean ± 95% confidence intervals) of Southern hake in Falkland Islands waters.

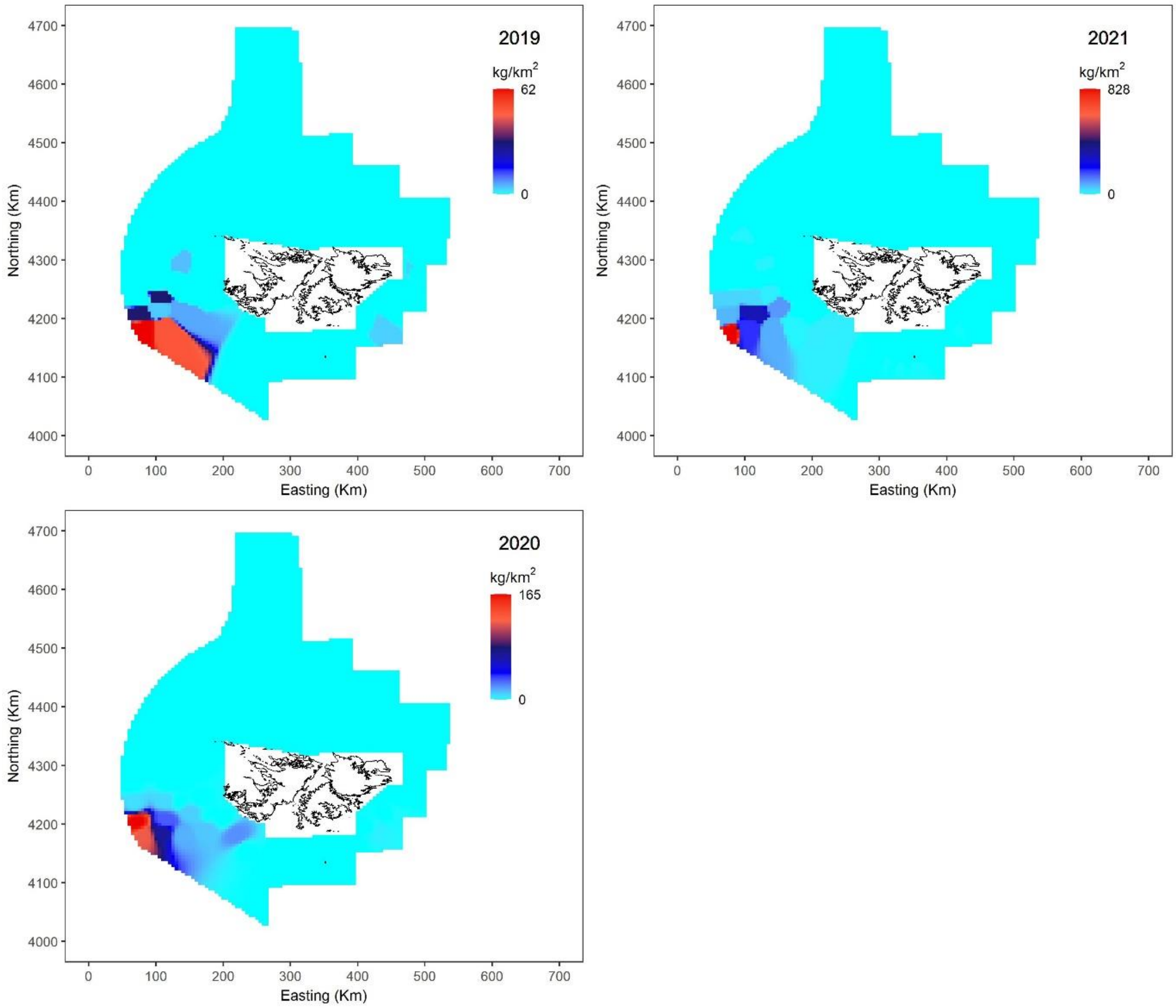
Year	Survey	Trawls (n)	Swept area (km^2)	Effort (h)	Catch (kg)	CPUE (kg/h)	Biomass (t)
2010	Groundfish	87	17.04	87.52	821.57	9.39	5096.76 (3910.63–6443.37)
	D. gahi	55	42.29	109.27	0.00	0.00	
	Total	142	59.34	196.78	821.57	4.17	
2011	Groundfish	88	17.21	88.00	754.44	8.57	5223.77 (3445.99–8095.63)
	D. gahi	58	40.04	110.63	18.26	0.17	
	Total	146	57.26	198.63	772.70	3.89	
2015	Groundfish	89	16.72	90.17	323.05	3.58	2961.07 (1750.69–4350.03)
	D. gahi	57	46.90	111.50	34.35	0.31	
	Total	146	63.61	201.67	357.40	1.77	
2016	Groundfish	90	17.64	91.42	215.41	2.36	1971.72 (1204.90–2963.73)
	D. gahi	56	54.46	107.92	30.93	0.29	
	Total	146	72.10	199.33	246.34	1.24	
2017	Groundfish	90	18.52	92.00	178.93	1.94	1829.09 (1021.33–2478.36)
	D. gahi	58	54.09	117.00	17.31	0.15	
	Total	148	72.62	209.00	196.24	0.94	
2018	Groundfish[a]	97	20.47	96.42	267.96	2.78	1453.02 (978.54–1947.08)
	D. gahi	59	36.87	100.83	32.60	0.32	
	Total	156	57.35	197.25	300.56	1.52	
2019	Groundfish	79	17.22	79.00	41.30	0.52	425.70 (88.45–577.12)
	D. gahi	52	72.70	97.05	10.00	0.10	
	Total	131	89.93	176.05	51.30	0.29	
2020	Groundfish[a]	80	17.04	79.95	89.38	1.12	593.71 (230.37–868.25)
	D. gahi	59	86.80	112.52	5.90	0.05	
	Total	139	103.84	192.47	95.28	0.50	
2021	Groundfish	80	16.43	79.48	240.12	3.02	1943.34 (919.34–2941.07)
	D. gahi	55	90.65	111.22	23.68	0.21	
	Total	135	107.07	190.70	263.80	1.38	
2022	Groundfish	42	9.22	41.90	95.14	2.27	920.22 (574.62–1471.85)
	D. gahi	60	86.75	119.08	15.01	0.13	
	Total	102	95.97	160.98	110.15	0.68	

[a]An additional one-day transect of four trawls was taken in shallow inshore waters to sample for juvenile toothfish. These four trawls were not included in analyses as their locations were not relevant to the distribution of Southern hake. Note that groundfish February surveys were not conducted in 2012, 2013, and 2014.

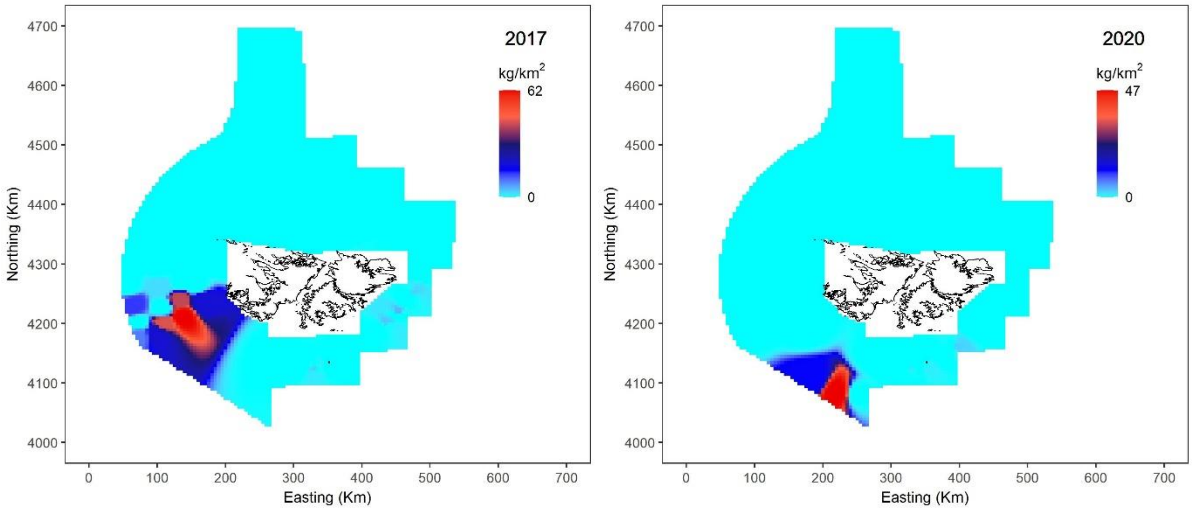
Appendix V. Densities of Southern hake modelled by inverse distance weighting in the FICZ, during the February 2010–2022 groundfish and Patagonian squid pre-season surveys.



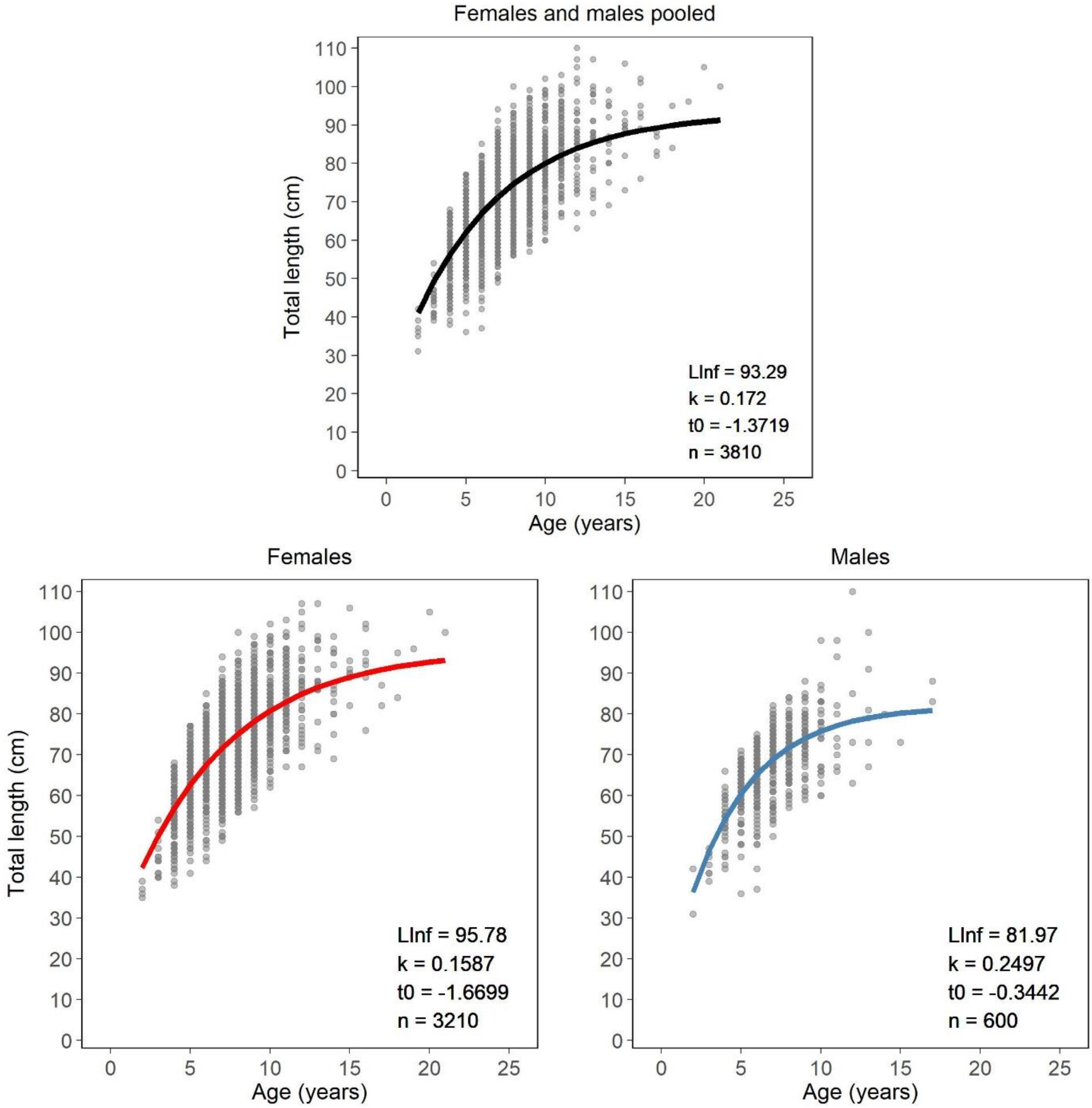
Appendix V. *continued…*



Appendix VI. Densities of Southern hake modelled by inverse distance weighting in the FICZ, during the July 2017 and July 2020 groundfish and Patagonian squid pre-season surveys.



Appendix VII. von Bertalanffy age-length relationship of female and male Southern hake collected in the FICZ.

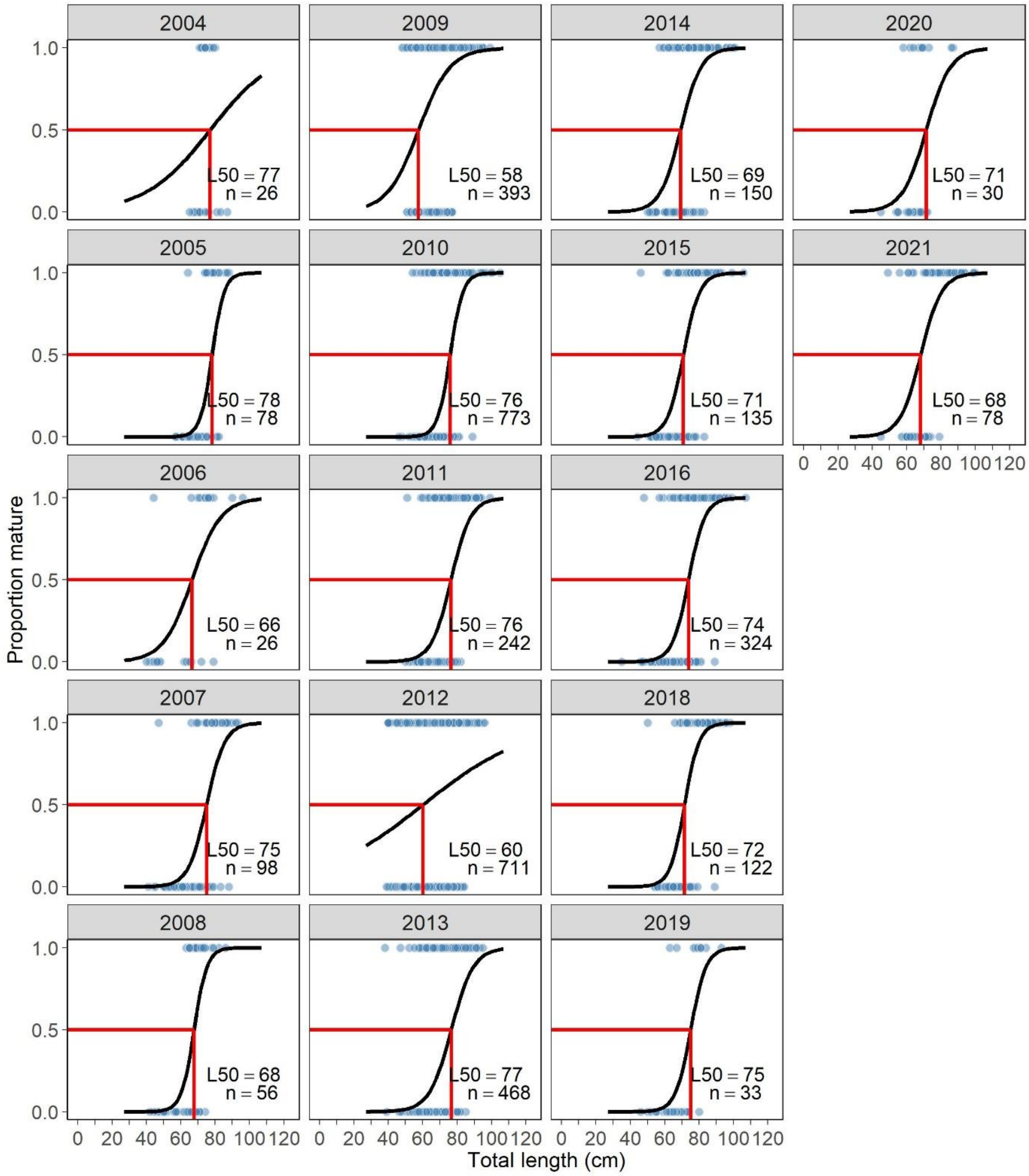


Appendix VIII. Southern hake von Bertalanffy length-at-age parameters for curvature (k), age at length zero (t_0), and asymptotic length (L_{Inf}), by year and sex, with 95% confidence intervals. Data were not available in some years. Age was determined by MFRI staff.

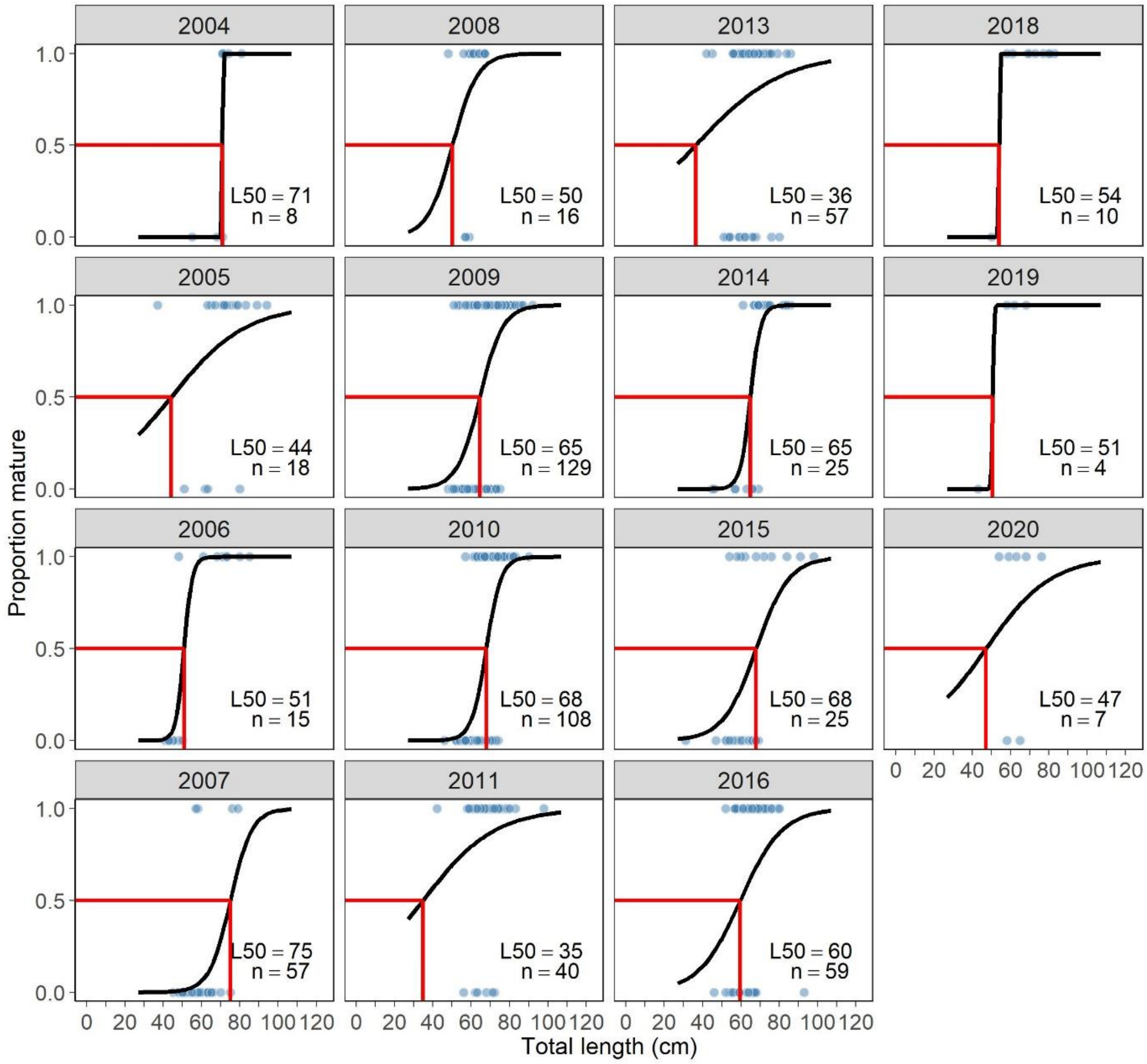
Sex	Year	n	k	t_0 (years)	L_{Inf} (cm)
	2002	369	0.284 (0.210 - 0.360)	0.410 (-0.514 - 1.044)	85.738 (82.126 - 91.320)
	2004	127	0.296 (0.210 - 0.393)	0.044 (-0.769 - 0.663)	85.615 (80.558 - 93.802)
	2005	106	0.219 (0.072 - 0.350)	-0.493 (-3.997 - 0.729)	92.103 (82.887 - 137.336)
	2006	28	0.187 (0.084 - 0.326)	0.722 (-0.887 - 1.715)	103.786 (87.440 - 146.147)
	2007	71	0.097 (0.017 - 0.196)	-1.677 (-8.566 - 1.275)	107.348 (88.779 - 269.787)
	2008	65	0.122 (0.026 - 0.240)	0.833 (-2.022 - 2.291)	113.698 (88.642 - 289.760)
F	2009	195	0.148 (0.081 - 0.223)	-0.277 (-3.146 - 1.420)	94.887 (86.761 - 113.623)
	2011	189	0.122 (0.027 - 0.236)	-1.782 (-6.015 - 0.249)	111.009 (92.022 - 247.767)
	2012	203	0.201 (0.112 - 0.299)	-0.239 (-2.196 - 0.917)	97.587 (89.442 - 116.728)
	2013	299	0.276 (0.141 - 0.423)	-0.070 (-2.511 - 1.199)	84.766 (79.615 - 98.293)
	2016	165	0.121 (0.043 - 0.207)	-1.470 (-4.391 - 0.103)	115.979 (98.139 - 192.339)
	2018	122	0.195 (0.122 - 0.273)	-0.455 (-2.542 - 0.826)	95.802 (90.442 - 106.424)

Sex	Year	n	k	t_0 (years)	L_{Inf} (cm)
	2002	53	0.103 (0.015 - 0.830)	-6.274 (-16.407 - 2.272)	94.562 (72.128 - 241.179)
	2003	49	0.281 (0.046 - 0.588)	-0.350 (-8.239 - 1.812)	80.499 (73.969 - 140.223)
	2004	26	0.763 (0.136 - 1.979)	2.308 (-3.299 - 3.384)	74.236 (70.094 - 98.060)
	2007	22	0.379 (0.076 - 0.769)	2.813 (-0.170 - 3.865)	71.830 (63.037 - 133.301)
	2008	16	0.331 (0.041 - 0.811)	2.305 (-5.353 - 4.394)	69.961 (63.832 - 139.897)
	2009	54	0.390 (0.207 - 0.650)	1.989 (-0.340 - 3.206)	74.576 (70.622 - 82.070)
M	2010	34	0.163 (0.024 - 0.374)	-0.062 (-8.906 - 2.989)	92.264 (79.775 - 206.611)
	2011	48	0.051 (0.009 - 0.323)	-4.380 (-7.708 - 0.999)	163.844 (84.848 - 628.647)
	2012	30	0.135 (0.014 - 0.596)	-1.813 (-9.180 - 2.555)	100.940 (74.830 - 351.613)
	2014	25	0.160 (0.023 - 0.368)	-0.790 (-4.781 - 1.089)	102.095 (81.062 - 303.680)
	2015	36	0.121 (0.056 - 0.222)	-0.919 (-2.840 - 0.539)	116.873 (92.033 - 170.219)
	2017	18	0.627 (0.278 - 1.622)	1.990 (-0.202 - 3.158)	75.062 (68.546 - 83.317)
	2018	10	0.458 (0.310 - 0.642)	1.997 (0.898 - 2.678)	81.898 (78.664 - 85.918)

Appendix IX. Binomial logistic regressions of juvenile (0) or adult (1) maturity ogives vs. length for female Southern hake. Red lines indicate the intercept for length at 50% adulthood, corresponding to Fig. 7. Note the gaps in some years when the model did not fit due to limited data.



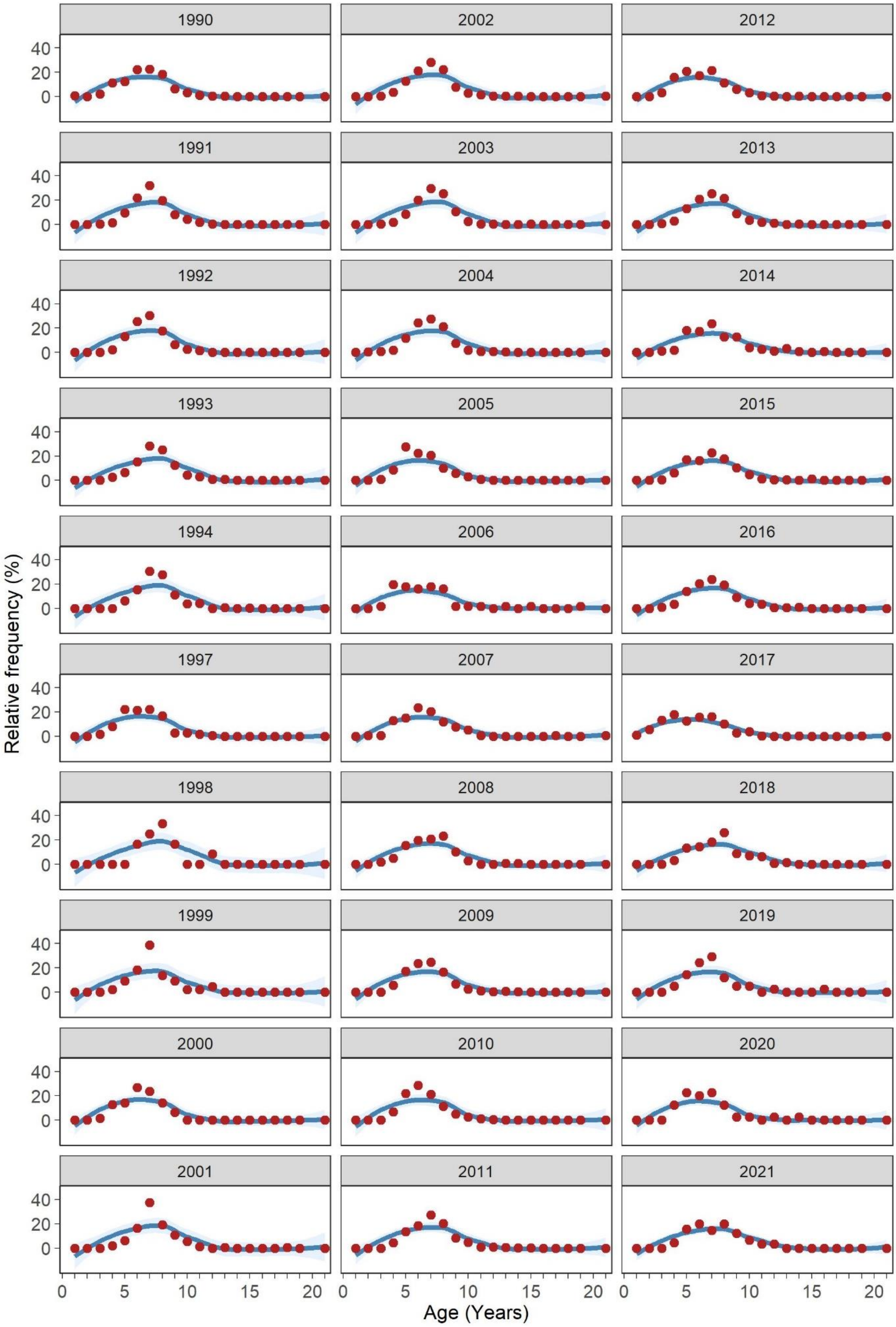
Appendix X. Binomial logistic regressions of juvenile (0) or adult (1) maturity ogives vs. length for male Southern hake. Red lines indicate the intercept for length at 50% adulthood, corresponding to Fig. 7. Note the gaps in some years when the model did not fit due to limited data.



Appendix XI. Number of Southern hake individuals sampled for length frequency distributions, corresponding to individuals caught randomly by finfish (A– and W–licences) and experimental (E–licence) vessels from January through May in the FICZ.

Year	Females (n)	Males (n)
2004	26	8
2005	78	18
2006	24	11
2007	98	57
2008	56	16
2009	374	115
2010	773	108
2011	240	39
2012	711	76
2013	468	57
2014	150	25
2015	135	25
2016	324	59
2017	203	24
2018	122	10
2019	33	4
2020	30	7
2021	78	8

Appendix XII. Catch at age of female Southern hake in Falkland Islands waters by finfish (A–, G–, and W–licences) and experimental (E–licence) vessels, with LOESS smooths ± 95% confidence intervals (LOESS; span = 1, degree = 2).



Appendix XIII. Catch at age of male Southern hake in Falkland Islands waters by finfish (A–, G–, and W–licences) and experimental (E–licence) vessels, with LOESS smooths ± 95% confidence intervals (LOESS; span = 1, degree = 2).