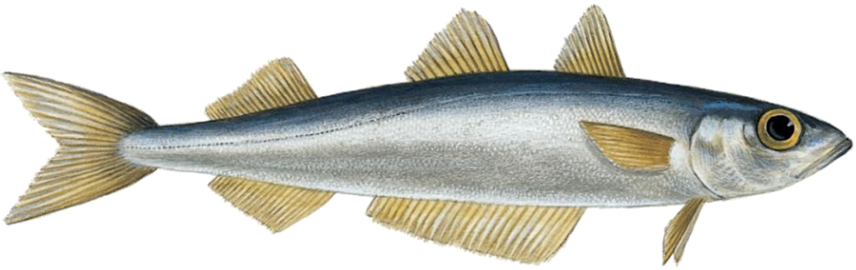
Stock Assessment of southern blue whiting (*Micromesistius australis*) in the Falkland Islands

SA - 2022 - BLU



Jorge E. Ramos, Andreas Winter

Natural Resources - Fisheries
Falkland Islands Government
Stanley, Falkland Islands

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Andrea Clausen
Director of Natural Resources
Falkland Islands

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Jorge E. Ramos*, Andreas Winter

Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, Bypass Road, Stanley FIQQ 1ZZ, Falkland Islands

*jeramos@naturalresources.gov.fk

Summary

Stock assessment of southern blue whiting *Micromesistius australis* was undertaken by commercial catch data analyses, the ICES category 5 advice rule for Total Allowable Catch, and the Length-Based Indicator (LBI) method. Commercial catches of southern blue whiting in Falkland Islands licenced fisheries were 23.6 tonnes in 2021, the lowest catch since 1990. The calamari X–licence accounted for 89.7%, and the finfish (A–, G–, and W–) licences accounted for 10.2% of the commercial southern blue whiting catch. LBI suggested that conservation of large individuals was mostly positive since 2002, consistent with yearly patterns of asymptotic lengths and length at 50% maturity for both females and males. Conservation of immature individuals has been poor since 2009–2010. However, LBI results may be affected by the closure of the fishery in spawning grounds, which limits access to biological samples of spawning individuals and juveniles, and due to no fishery targeting southern blue whiting since 2017. Patterns of L_{Inf} and L50, the presence of small individuals in recent years, and high densities of southern blue whiting at sizes near to commercial size in spawning grounds during a survey conducted in September 2022 suggest that the stock is recovering slowly.

The ICES category 5 TAC calculated at 406 t for Falkland Islands finfish trawl fisheries, corresponds to the average catch of the last three years with a 20% cap reduction of the current year TAC_{2022} (508 t). The recommendation then is to set the TAC at 406 t for 2023, under the assumption that southern blue whiting will continue to be taken only as trawl bycatch during 2023. However, a statutory TAC of 2,000 t is maintained for S licence and may be augmented for the purpose of an exploratory survey.

1. Introduction

Southern blue whiting *Micromesistius australis* (Norman 1937; Gadidae) is a bentho-pelagic fish that occurs at 100 to 800 m (Aguayo et al. 2010; Froese & Pauly 2019) in temperate shelf waters of the Southeast Pacific between 42°S and 57°S (southern Chile), and temperate shelf waters of the Southwest Atlantic between 37°S and 55°S (Argentina and Falkland Islands). Spawning occurs during September and October to the south of the Falkland Islands at 200–300 m depths (Shubnikov et al. 1969; Pájaro & Macchi 2001; Macchi et al. 2005). Spawning grounds vary in size and location depending on the intensity of the Falkland Current (Arkhipkin et al. 2009, 2012); other spawning grounds occur at 200–300 m depths off the southern coast of Chile, between Golfo de Penal and Peninsula de Tres Mortes (Arkhipkin et al. 2009). Part of the population migrates from the Atlantic in June-July to spawn in Chilean waters in August, and by the middle of November moves back to Atlantic feeding grounds (Lillo et al. 1999). Individuals that spawn in Falkland Islands waters move to the Patagonian Shelf and remain in that area until December-January before moving further south to feeding grounds in the Scotia Sea (Barabanov 1982). Mixing between both populations may occur when immature individuals share common feeding grounds in the Scotia Sea during the Antarctic summer (Perrotta 1982; Barabanov et al. 1984; Arkhipkin et al. 2009). Connectivity between the Southwest Atlantic and Southeast Pacific was confirmed by otolith chemistry (Arkhipkin et al. 2009) and mitochondrial DNA analyses (Shaw 2003, 2005). Therefore, southern blue whiting from the Falkland Islands, Argentina and Chile may be a single stock.

In the Southwest Atlantic, southern blue whiting exploitation started in 1977 by Polish factory trawlers. Starting in 1987, Polish and Bulgarian trawlers licensed by the Falkland Islands Government targeted southern blue whiting in Falkland Islands waters, whereas large factory trawlers continued fishing in the southern part of the Patagonian Shelf in the Argentine EEZ (Agnew 2002; Arkhipkin et al. 2022). Heavy exploitation of the stocks caused the decline in catches in the Southwest Atlantic since the early 1990's, and its collapse in 2009 (Navarro et al. 2014; Falkland Islands Government 2021). Conservation measures were implemented by the Falkland Islands Government since 2010, including seasonal closure of the spawning grounds and TAC reduction (Falkland Islands Government 2021), and the stock has started to show signs of slow recovery (Ramos & Winter 2021; Arkhipkin et al. 2022).

2. Methods

Stock assessment of southern blue whiting was undertaken by two approaches in parallel: the ICES advice rules (ICES 2012, 2018) for Total Allowable Catch, and the Length-Based Indicator (LBI) method (MEP 2020). Both approaches were calculated using commercial fishery data. Additionally, biomass estimates, biomass ratios, and spatial distribution of southern blue whiting were examined from scientific surveys carried out in austral winter, during July 2017 (Gras et al. 2017; Winter et al. 2017) and July 2020 (Randhawa et al. 2020; Winter et al. 2020). CASAL (Bull et al. 2012) was no longer implemented given that no fishery has targeted southern blue whiting in the Falkland Islands Conservation Zones (FICZ) since 2016, and limited catch, abundance index (CPUE), and biological data prevent reliable estimates of biomass, spawning stock biomass (SSB), and Maximum Sustainable Yield (MSY) (Appendix I).

2.1. Commercial fishery data

Commercial fishing around the Falkland Islands was not recorded separately from other parts of the Southwest Atlantic prior to 1982 and catch data by species were reported systematically from 1987 onwards only (Falkland Islands Government 1989). Therefore, southern blue whiting catch data were examined from 1987 to 2021 (Falkland Islands Government[1]; Falkland Islands Government 2021), Argentina (Government of Argentina[2]; Sánchez et al. 2012; Navarro et al. 2014, 2019), and Chile (Government of Chile[3]; SERNAPESCA 1990, 2000, 2011, 2021). LOESS (span = 0.75, degree = 2) was implemented to examine the pattern of association between the Southwest Atlantic (Falkland Islands and Argentina) and the Southeast Pacific (Chile) commercial annual catches of southern blue whiting from 1987 through 2021. Commercial catches and discard of southern blue whiting were examined by licence type for 2021 in the FICZ.

CPUE was calculated as the sum of southern blue whiting catches divided by the sum of effort. Annual CPUE series were calculated for four fleets with fishing activity in the FICZ during different periods of time: 1) Polish fleet (A–, and W–licences) comprised of bottom

[1] http://www.fig.gov.fk/fisheries/publications/fishery-statistics
[2] https://www.agroindustria.gob.ar/sitio/areas/pesca_maritima/desembarques/
[3] http://www.sernapesca.cl/informes/estadisticas

trawlers with fishing activity from November to January, from 1987 to 1996; 2) Surimi fleet (S–licence) comprised of semi-pelagic trawlers with fishing activity in the first half of the year (January to June), from 2000 to 2016; 3) Surimi fleet (S–licence) comprised of semi-pelagic trawlers with fishing activity in the second half of the year (November and December), from 1999 to 2014; and 4) Finfish fleet (A–, and W–licences) comprised of bottom trawlers with fishing activity from January to June, and in November and December, from 1997 to 2021. The first and second halves of the year were examined separate for the surimi fleet because this fleet targets the feeding aggregations in the first part of the year, and the densely aggregated post-spawning aggregations in the second half of the year in Falkland Islands waters (Falkland Islands Government 2013). The Polish fleet also targeted southern blue whiting (Falkland Islands Government 2013), while the finfish fleet caught this species as bycatch. The monthly distribution of CPUE in the FICZ during 2021 were examined for the W–licence, which was the only finfish licence with southern blue whiting catches in 2021.

2.2. ICES Total Allowable Catch

In 2020, southern blue whiting was included in a 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. The primary recommendation from the MEP report is a category 3 assessment framework using a 2/3 rule, in which next year’s advised TAC is increased or decreased by a ratio equivalent to the mean of the most recent two years over the mean of the previous three years of a biomass index. Category 3 thus requires an unbiased biomass time series of at least the last five years. For the Falkland Islands fisheries, the necessary time frame is provided by the February joint surveys (Ramos & Winter 2022). However, February is not a month of peak abundance for southern blue whiting in Falkland Islands waters (Barabanov 1982), and a biomass index calculated from the February surveys may not be reliable for this stock. Southern blue whiting has not been targeted by any commercial fishery in the FICZ since 2016 and little commercial bycatch has been taken since; CPUE calculated from the commercial catch would thus not serve as an abundance index either. The alternative to category 3 is category 5, which consists of the average catches of the 3 previous years (MEP 2020), further limited to an 'uncertainty cap' of ± 20% (ICES 2018) with respect of the TAC set for the current year (TAC_{2022} = 508 t; Ramos & Winter 2021):

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

Category 5 TAC was calculated based on in-zone catches, excluding experimental (E–licence) and out-of-zone catches (O–licence) (Appendix II).

2.3. Length Based Indicators

MEP (2020) recommended exploring ancillary stock status information from ICES data-limited methods. The Length-Based Indicator method (LBI) was used to provide a suite of indicators for conservation of immature fish, large individuals, mega-spawners, optimal yield, and MSY based on combinations of catch-at-size distributions, and life-history parameters such as L_{Inf} (asymptotic length; Haddon 2001) and L50 (length at 50% maturity; Cope & Punt 2009). L_{Inf} and L50 parameters were assessed for females and males separately.

LBI method was applied to all years from which southern blue whiting length and age data were available and reported as random samples (FIFD database codes R and S), i.e., years 1990 to 2021 for length data, and years 2002 to 2018 for age data. Because finfish trawls are restricted to larger meshes than calamari trawls, only length and age data from finfish (A–, G–, and W–licences), surimi (S–licence), and experimental (E–licence) vessels fisheries were used, to avoid biasing length-frequency distributions if proportionally more samples are recorded from one fishery or another in different years. Skate and *Illex* trawls were also excluded because their different targets could also relate to characteristically different length-frequency distributions of southern blue whiting.

LBI method indicators were then selected and scored using Tables 2.1.1.4.1 and 2.1.2.2 in ICES (2015) as templates:

1) Length at half the modal catch length should be bigger than L50, for conservation of immature fish (L_C / L50 > 1). Note that length at half the modal catch length may be poorly defined if the catch length-frequency distribution is not smooth and unimodal.
2) Length at cumulative 25th percentile of catch numbers should be bigger than L50, for conservation of immature fish ($L_{25\%}$ / L50 > 1).

3) Mean length of the largest 5% of individuals in the catch should be at least 80% of the asymptotic length, as a benchmark that enough large individuals are in the stock ($L_{max5\%}$ / L_{Inf} > 0.8).

4) 'Mega-spawners' should comprise at least 30% of the catch (thus implicitly represent at least 30% of the stock), as large, old fish disproportionately benefit the resilience of the population (Froese 2004) (P_{mega} > 0.3). Mega-spawners are defined as individuals larger than optimum length (L_{Opt}) + 10%, where L_{Opt} is described as the length at which growth rate is maximum (ICES 2015), or the length at which total biomass of a year-class reaches its maximum value (Froese & Binohlan 2000). $L_{Opt} = 3 \cdot L_{Inf} \cdot (3 + Mk^{-1})^{-1}$ (Beverton 1992), where M is instantaneous natural mortality, k is the rate of curvature of the von Bertalanffy growth function, and the ratio Mk^{-1} is set in WKLIFE V software (ICES 2015) at the standard constant of 1.5 (Jensen 1996).

5) Mean length of individuals larger than L_C (L_{meanC}) should be approximately equal to L_{Opt}, for optimal yield (L_{meanC} / L_{Opt} ≈ 1).

6) L_{meanC} should be equal or bigger to the length-based proxy for MSY ($L_{F=M}$), for producing maximum sustainable yield (L_{meanC} / $L_{F=M}$ ≥ 1). $L_{F=M}$ implements the premise that MSY is attained when fishing mortality equals natural mortality (Froese et al. 2018), and in WKLIFE V software (ICES 2015) is computed as $(3 \cdot L_C + L_{Inf})/4$.

Margins of variability of the six indicators were estimated by randomly re-sampling 10,000× on the normal distribution each year's fits of L_{Inf} and L50. Indicators were scored against the 'traffic light' scale (ICES 2015) with reference criteria > 1.0 for conservation of immature fish, > 0.8 for conservation of large fish, and > 0.3 for conservation of mega-spawners. The score was green if the lower 95% quantile of the re-sampled iterations was > 1.0, > 0.8, and > 0.3, yellow if 1.0, 0.8, and 0.3 were between the lower and upper 95% quantiles, and red if the upper 95% quantile of the re-sampled iterations was < 1.0, < 0.8, and < 0.3. The use of the margins of variability means that same empirical values of indicators may be scored different colours in different years. Reference criterion ≈ 1.0 for optimal yield was green if the lower and upper 95% quantiles spanned 1.0, yellow if the lower and upper 95% quantiles spanned 0.9 (the threshold used in ICES 2015) without spanning 1.0, and red otherwise. Reference criterion ≥ 1.0 for MSY was scored the same as > 1.0, except that empirical values ≥ 1.0 were automatically green.

2.3.1. Length-age relationship

The von Bertalanffy growth function (R package 'fishmethods'; Nelson 2019) was used to fit southern blue whiting length-at-age data available in the FIFD database, from individuals sampled randomly and non-randomly in finfish (A–, G–, and W–licences), experimental (E–licence), and surimi (S–licence) vessels. Southern blue whiting length and age data were examined for years 2002–2018, with status of age data advised 'Unknown' (Lee et al. 2020), as verification of these ages is in progress. Growth model parameters (L_{Inf}, k, and t_0) were calculated for females and males using nonlinear least square regression. A likelihood ratio test (R package 'fishmethods'; Nelson 2019) was used to test whether the von Bertalanffy growth function was significantly different between females and males. Variabilities of the growth model parameters were estimated by bootstrapping; residuals of the model fits were randomly re-sampled 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 trend of von Bertalanffy L_{Inf} was calculated by LOESS (span = 0.75, degree = 2).

2.3.2. Length and age at 50% maturity

Overall and yearly length at 50% maturity (L50) was calculated as the mid-point of the binomial logistic regression of maturity ogive 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. Gonadal maturity is cyclical as fish pass from post-spawning to resting phase, and definitive maturity assignments can only be made that stage I is immature and stages III or higher are mature (A. Arkhipkin, FIFD, *pers. comm.*). Therefore, maturity assignment was simplified to a dichotomous classification of 0) juvenile, including maturity stage I, and 1) adult, including maturity stages III to VIII, omitting stage II. Annual L50s were calculated from randomly sampled individuals collected through the FICZ under finfish (A–, G–, and W–licences), surimi (S–licence), and experimental (E–licence) vessels through the year, from 1990 through 2021. Trends of annual L50 were calculated with LOESS (span = 0.75, degree = 2). Overall and yearly age at 50% maturity (A50) was calculated for females and males separately, by predicting age corresponding to L50 using the inversed von Bertalanffy equation.

2.3.3. Catch at length

Length frequencies were examined yearly, from 1990 through 2021, for females and males to describe patterns in catch at length through time. Lengths of individuals sampled randomly (FIFD database codes R and S) and caught by finfish (A–, G–, and W–licences), surimi (S–licence), and experimental (E–licence) vessels throughout the FICZ from January through December were included in the analysis. Yearly length frequencies were compared with yearly L50 to assess if the catch was mainly comprised of immature or mature individuals.

3. Results

3.1. Commercial fishery data

Southern blue whiting catches in Falkland Islands waters have averaged 21,323 t per year, and represent approximately 25% of the aggregate Falkland Islands, Argentine, and Chilean combined annual catches since 1987. The highest catch in Falkland Islands waters was reported in 1990 (71,876 t) and the lowest catch was reported in 2021 (23.6 t); low catches in recent years may be associated to finfish vessels targeting other commercial species in areas where southern blue whiting are not common (Falkland Islands Government 2021). Combined catches across nations increased from 1987 through 1993, and declined towards 2010. Combined catches were relatively low and constant from 2011 through 2021 (annual average of 22,515 t; Fig. 1).

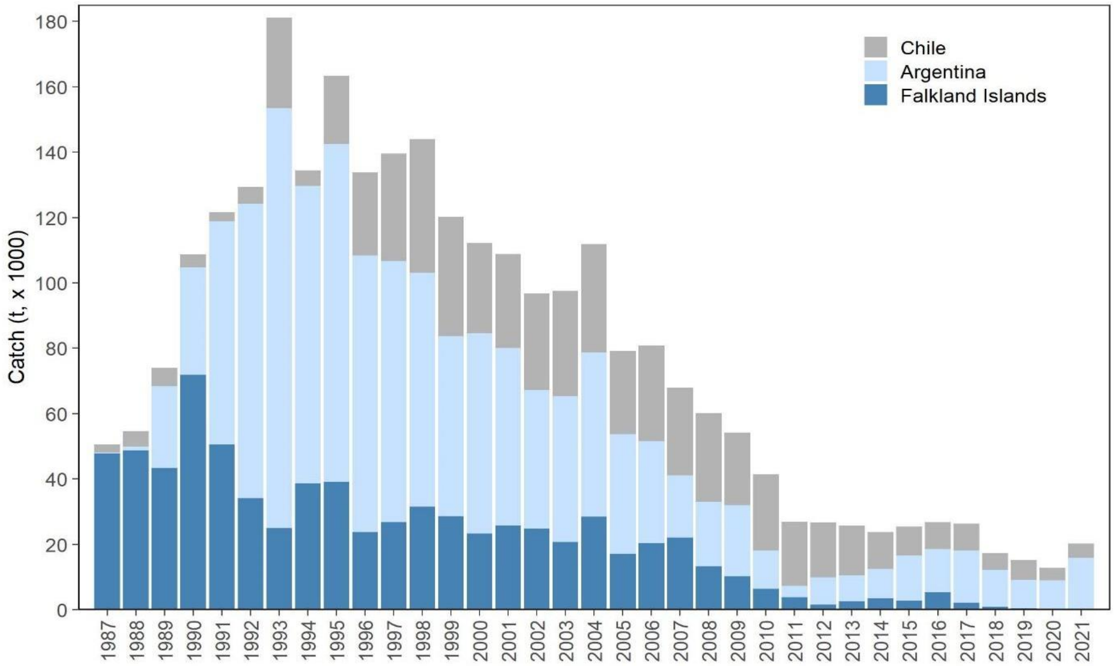

Fig. 1. Annual commercial catch of southern blue whiting in Falkland Islands, Argentine and Chilean waters. Falkland Islands commercial catch data exclude experimental (E–licence) and out-of-zone (O–licence) licences from 1990; earlier than 1990 these licences were not designated.

Annual catches in the Southwest Atlantic had a significant positive correlation with annual catches in the Southeast Pacific, up to an approximately intermediate level. Southwest Atlantic catches higher than this intermediate level showed a weak (non-significant) negative correlation with Southeast Pacific catches. However, the seven years of the interval 1987 to 1992, and 1994, spanned a range of catch totals in the Southwest Atlantic corresponding to uniformly low catches in the Southeast Pacific. These years were the earliest years of the time series, possibly indicating that the Chilean fishery for southern blue whiting had not yet commercially developed. The single year 1993 in this interval contrasted by having the highest Southwest Atlantic catches of the entire study period and among the highest Southeast Pacific catches (Fig. 2; Appendix II). These comparisons suggest that the relationship between Southwest Atlantic and Southeast Pacific catches (and by extension of their available biomasses) may be governed by thresholds that trigger changes of state under different conditions.

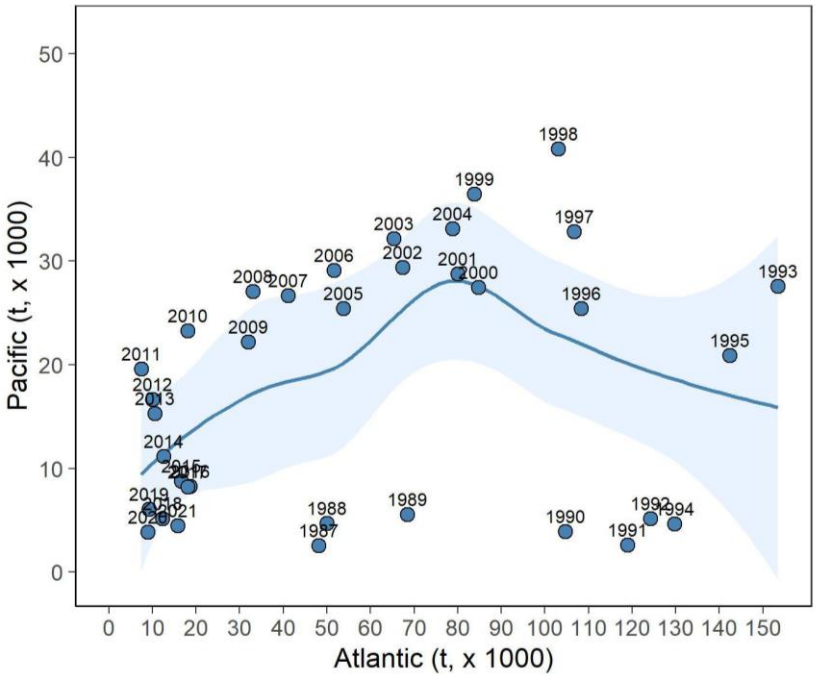

Fig. 2. Southeast Pacific (Chile) vs. Southwest Atlantic (Falkland Islands + Argentina) annual commercial catches of southern blue whiting from 1987 to 2021, with LOESS smooth ± 95% confidence intervals (LOESS; span = 0.75, degree = 2).

The Polish fleet had CPUE values in the range of 2,101 kg/h to 4,116 kg/h from 1987 to 1996, with no evident trend. Finfish catches had a maximum of 4,441 kg/h in 1997, followed by a steep decline to reach only 313 kg/h in 2000; CPUE were on average 220 kg/h from 2000 to 2021 as southern blue whiting have been taken as bycatch by this fleet. The surimi fleet in the first half of the year showed a decline from 6,683 kg/h in 2000 to 1,384 kg/h in 2016. The surimi fleet in the second half of the year had higher CPUE values compared with the other fleets; CPUE increased from 9,103 kg/h in 1999 to 13,273 kg/h in 2005, followed by a decline to reach 6,603 kg/h in 2016 (Fig. 3).

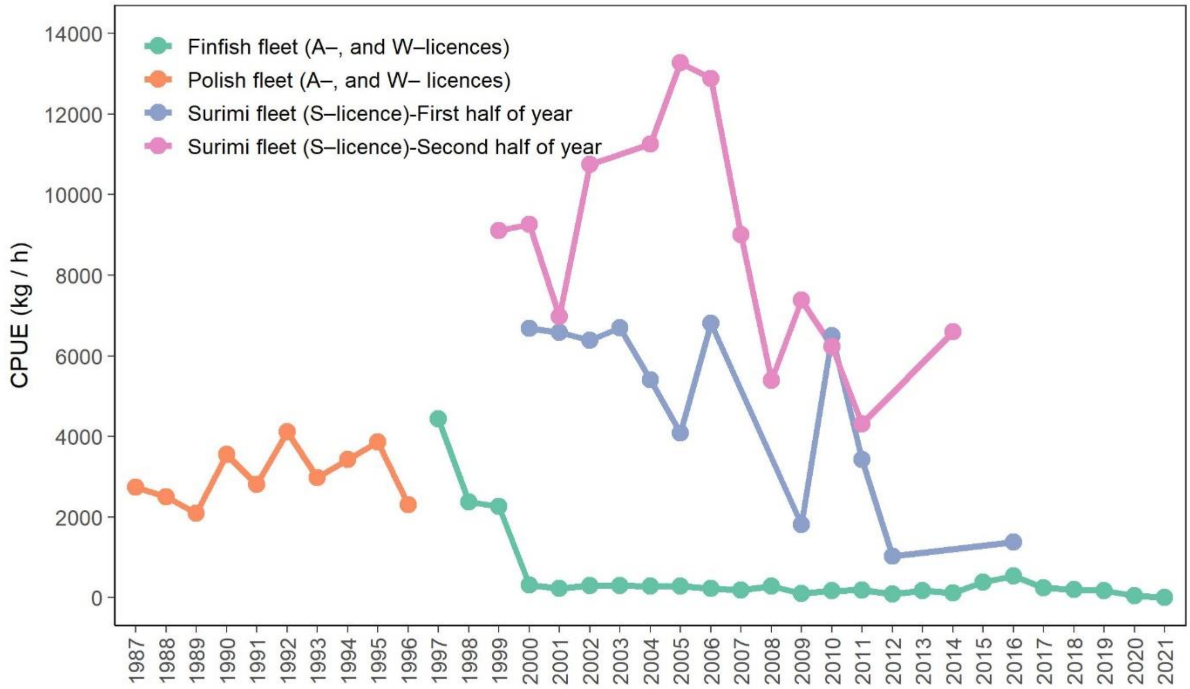

Fig. 3. Annual CPUE of southern blue whiting in Falkland Islands (FK) waters, calculated from the Polish fleet (A–, and W–licences), surimi fleet (S–licence) during the first and second halves of the year, and finfish fleet (A–, and W–licences).

During 2021 a total of 86.5 t of southern blue whiting were reported caught in Falkland Islands waters, of which 23.6 t were reported under commercial licences, i.e., excluding the experimental E–licence. The calamari X–licence accounted for 24.5% of the total southern blue whiting catch, and the finfish (W–licence) accounted for 2.8% of the total southern blue whiting catch (Table I). Most southern blue whiting catches in 2021 were contributed during surveys carried out in February, July, and October under the experimental E–licence (72.7%; Table I). Considering only the commercial catch (23.6 t), the calamari X–licence accounted for 89.7% of the southern blue whiting catch, and the finfish (W–licence) accounted for 10.2% of the southern blue whiting catch. Southern blue whiting catches by W–licensed vessels occurred to the southwest of the FICZ (Appendix III).

Table I. Catch proportion of southern blue whiting by licence type in Falkland Islands waters during 2021.

Licence	Target species	Catch (t)	Catch (%)	Discard (t)	Proportion discarded (%)
E	Experimental	62.888	72.70	3.238	5.15
X	Calamari 2nd season	21.189	24.50	20.885	98.57
W	Restricted finfish	1.735	2.01	0.066	3.80
G	Restricted finfish and *Illex*	0.338	0.39	0.067	19.82
A	Unrestricted finfish	0.330	0.38	0.310	93.94
C	Calamari 1st season	0.018	0.02	0.018	100.00
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
S[a]	Southern blue whiting and hoki	0.000	0.00	0.000	0.00
O	Outside Falkland Islands waters	0.000	0.00	0.000	0.00
Total		86.498	100.00	24.584	28.42

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

3.2. ICES Total Allowable Catch

The three-year average for the year 2023 under the ICES category 5 assessment framework was calculated at 195 t:

$$TAC\_5_{2023} = \overline{504 + 58 + 24} = 195.2$$

The 20% cap reduction of the current year TAC_{2022} (508 t; Ramos & Winter 2021) is 406.4 t. Given that the average catch of the last completed three years decreased beyond the 20% cap reduction of the current year TAC_{2022}, TAC for 2023 is set at 406 t.

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.

3.3. Length Based Indicators

Yearly 'traffic light' length indicators for females and males are summarized in Table II. Indicator L_C/L50, for conservation of immature fish, was positive (green) from 1991 to 2008; however, it was mostly negative (red) from 2009 to 2021 for females and males. Indicator $L_{25\%}$/L50, also for conservation of immature fish, was positive for females and males from 1990 to 2009; however, negative outcomes were common from 2010 to 2021 for both females and males. Indicator $L_{max5\%}/L_{Inf}$, for the conservation of large individuals, was mostly positive from 1990 to 2018 for both females and males. Indicator P_{mega}, for the presence of mega-spawners, was positive most years for females, except for negative outcomes in 2010, 2014, 2015, and 2018. Indicator P_{mega} was positive from 1990 to 2013, and negative from 2014 to 2018 for males. Indicator L_{meanC}/L_{Opt}, for optimal yield, was mostly positive for females from 1990 to 2009, and fluctuated between negative, of concern (yellow), and positive from 2010 to 2018. Indicator L_{meanC}/L_{Opt} was mostly positive for males from 1990 to 2011, and fluctuated between negative, of concern, and positive from 2012 to 2018. Indicator $L_{meanC}/L_{F=M}$, for maximum sustainable yield, was mostly positive for females and males in the time series, except for 2014, 2016, and 2018 with negative outcomes.

Table II. Southern blue whiting indicators by sex and year, with 'traffic light' scoring. L_C) Length at half the modal catch length; L50) Length at 50% maturity; $L_{25\%}$) Length at cumulative 25th percentile of catch; $L_{max5\%}$) Mean length of the largest 5% of individuals in the catch; L_{Inf}) Asymptotic average maximum body size; P_{mega}) Proportion of 'Mega-spawners' in the catch; L_{meanC}) Mean length of individuals larger than LC; L_{Opt}) Optimum length; $L_{F=M}$) Length-based proxy for MSY. Data were not available in some years (blank cells).

		Conservation				Optimal yield	MSY
Sex	Year	L_C / L50 >1.0	$L_{25\%}$ / L50 >1.0	$L_{max5\%}$ / L_{Inf} >0.8	P_{mega} >0.3	L_{meanC} / L_{Opt} ≈1.0	L_{meanC} / $L_{F=M}$ ≥1.0
	1990	1.02	1.04	0.95	0.47	1.14	1.03
	1991	1.12	1.15	0.99	0.76	1.20	1.02
	1992	1.20	1.23	1.01	0.92	1.27	1.02
	1993	1.23	1.23	0.98	0.90	1.28	1.01
	1994	1.28	1.26	0.98	0.97	1.31	1.01
	1995			1.00	0.97	1.36	1.01
	1996	1.34	1.34	0.99	0.96	1.37	1.02
	1997	1.29	1.29	0.97	0.90	1.33	1.02
	1998	1.35	1.22	0.99	0.86	1.37	1.02
	1999			1.00	0.93	1.40	1.03
	2000	1.46	1.46	1.03	1.00	1.44	1.02
	2001	1.25	1.30	1.02	0.98	1.36	1.08
	2002	1.46	1.44	1.04	0.89	1.46	1.03
	2003	1.16	1.22	1.02	0.87	1.31	1.10
	2004	1.24	1.30	1.02	0.95	1.35	1.09
F	2005	1.34	1.40	1.02	0.98	1.39	1.06
	2006	1.47	1.39	1.02	0.89	1.44	1.03
	2007	1.21	1.29	1.02	0.95	1.33	1.11
	2008	1.29	1.32	1.02	0.93	1.35	1.08
	2009	0.73	1.30	1.03	0.80	1.27	1.46
	2010	0.66	0.68	1.02	0.25	0.89	1.09
	2011	0.63	0.80	1.04	0.54	1.12	1.41
	2012	0.50	0.53	1.02	0.37	0.88	1.25
	2013	0.64	1.15	1.03	0.63	1.12	1.42

	2014	0.53	0.56	1.02	0.12	0.68	0.94
	2015	0.53	0.59	1.05	0.24	0.81	1.13
	2016	0.64	1.06	1.01	0.38	1.05	1.32
	2017	0.45	0.61				
	2018	0.63	0.66	0.87	0.05	0.68	0.83
	2019	0.60	0.65				
	2020	0.40	0.46				
	2021	0.61	0.63				

Table II. *continued…*

		Conservation				Optimal yield	MSY
Sex	Year	L_C / L50 >1.0	$L_{25\%}$ / L50 >1.0	$L_{max5\%}$ / L_{Inf} >0.8	P_{mega} >0.3	L_{meanC} / L_{Opt} ≈1.0	L_{meanC} / $L_{F=M}$ ≥1.0
	1990	1.04	1.07	0.99	0.56	1.20	1.04
	1991	1.13	1.13	0.99	0.79	1.23	1.01
	1992	1.19	1.19	1.01	0.84	1.29	1.02
	1993	1.22	1.20	0.98	0.86	1.28	1.00
	1994	1.20	1.23	0.98	0.97	1.29	1.03
	1995	1.33	1.30	0.99	0.94	1.36	1.01
	1996	1.39	1.36	1.01	0.95	1.40	1.02
	1997	1.35	1.32	0.98	0.90	1.36	1.02
	1998	1.19	1.22	0.98	0.84	1.30	1.07
	1999	1.47	1.35	1.01	0.94	1.42	1.02
	2000			1.05	1.00	1.47	1.02
	2001	1.34	1.40	1.01	0.97	1.36	1.06
	2002	1.60	1.57	1.04	0.90	1.48	1.02
	2003	1.27	1.33	1.03	0.90	1.31	1.08
	2004	1.35	1.38	1.03	0.94	1.34	1.06
M	2005	1.44	1.44	1.02	0.92	1.38	1.05
	2006	1.23	1.29	1.01	0.81	1.29	1.10
	2007	1.37	1.40	1.01	0.93	1.32	1.06
	2008	1.42	1.45	1.02	0.87	1.34	1.06
	2009	1.51	1.42	1.03	0.78	1.37	1.06
	2010	0.75	0.82				
	2011	0.79	0.99	1.04	0.60	1.19	1.43
	2012	0.60	0.67	1.02	0.35	0.92	1.29
	2013	0.77	1.35	1.04	0.66	1.19	1.46
	2014	0.64	0.71	1.00	0.09	0.70	0.95
	2015	0.64	0.77	1.03	0.19	0.86	1.17
	2016	1.21	1.21	0.97	0.18	1.04	0.97
	2017	1.30	0.80				
	2018	0.76	0.76	0.93	0.14	0.76	0.92
	2019	0.71	0.94				
	2020	0.51	0.60				
	2021	0.71	0.71				

3.3.1. Length-age relationship

The length-age relationship of females and males pooled (n = 5,357) gave the values: L_{Inf} = 59.15 cm, k = 0.2348, and t_0 = -0.6759 years (Appendix IV). Length and age of females (n = 2,592) ranged from 12 cm to 70 cm, and from 1 year to 29 years, respectively. The length-age relationship of females gave the values: L_{Inf} = 60.80 cm, k = 0.2298, and t_0 = -0.6696 years. Length and age of males (n = 2,765) ranged from 12 cm to 65 cm and from 1 year to 29 years, respectively. The length-age relationship of males gave the values: L_{Inf} = 56.92 cm, k = 0.2506, and t_0 = -0.6194 years (Appendix IV). Yearly von Bertalanffy parameters are summarized in Appendix V. Asymptotic lengths (L_{Inf}) increased significantly for females from 2002 to 2013, but not for males in any range of years although the pattern is similar (Fig. 4).

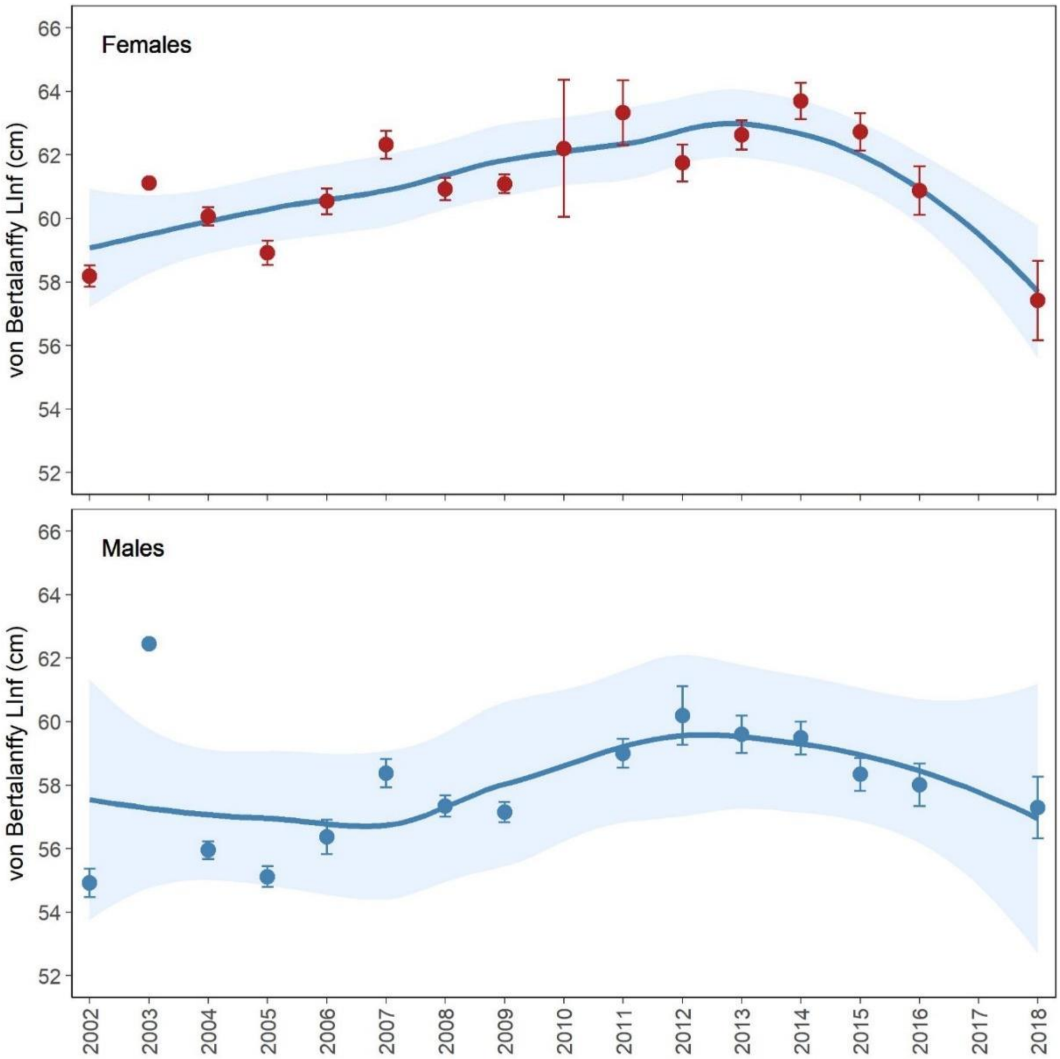

Fig. 4. Asymptotic lengths (L_{Inf}) ± 1 standard error calculated according to the von Bertalanffy growth function for female (red dots) and male (blue dots) southern blue whiting caught by finfish (A–, G–, and W–licences), experimental (E–licence), and surimi (S–licence) vessels in the FICZ through the year, from 2002 through 2018, with LOESS smooths ± 95% confidence intervals (LOESS; span = 0.75, degree = 2).

3.3.2. Length and age at 50% maturity

Over the time series 1990–2021, length at 50% maturity (L50) of females was 35.6 ± 0.09 cm total length (n = 57,261) and age at 50% maturity (A50) was 3.2 years old; L50 of males was 32.8 ± 0.06 cm total length (n = 81,180) and A50 was 2.8 years old. Therefore, immature individuals are inferred as < 3 years old and mature individuals are inferred as ≥ 3 years old. Annual L50 and A50 of females ranged from 23.8 cm and 1.5 years old in 2005 to 39.2 cm and 3.8 years old in 2019, respectively. Annual L50 and A50 of males ranged from 22.6 cm and 1.4 years old in 2005 to 38.3 cm and 3.8 years old in 1995. The L50 fit did not change significantly for females or males from 1990 through 2021 (Fig. 5; Appendixes VI–VII).

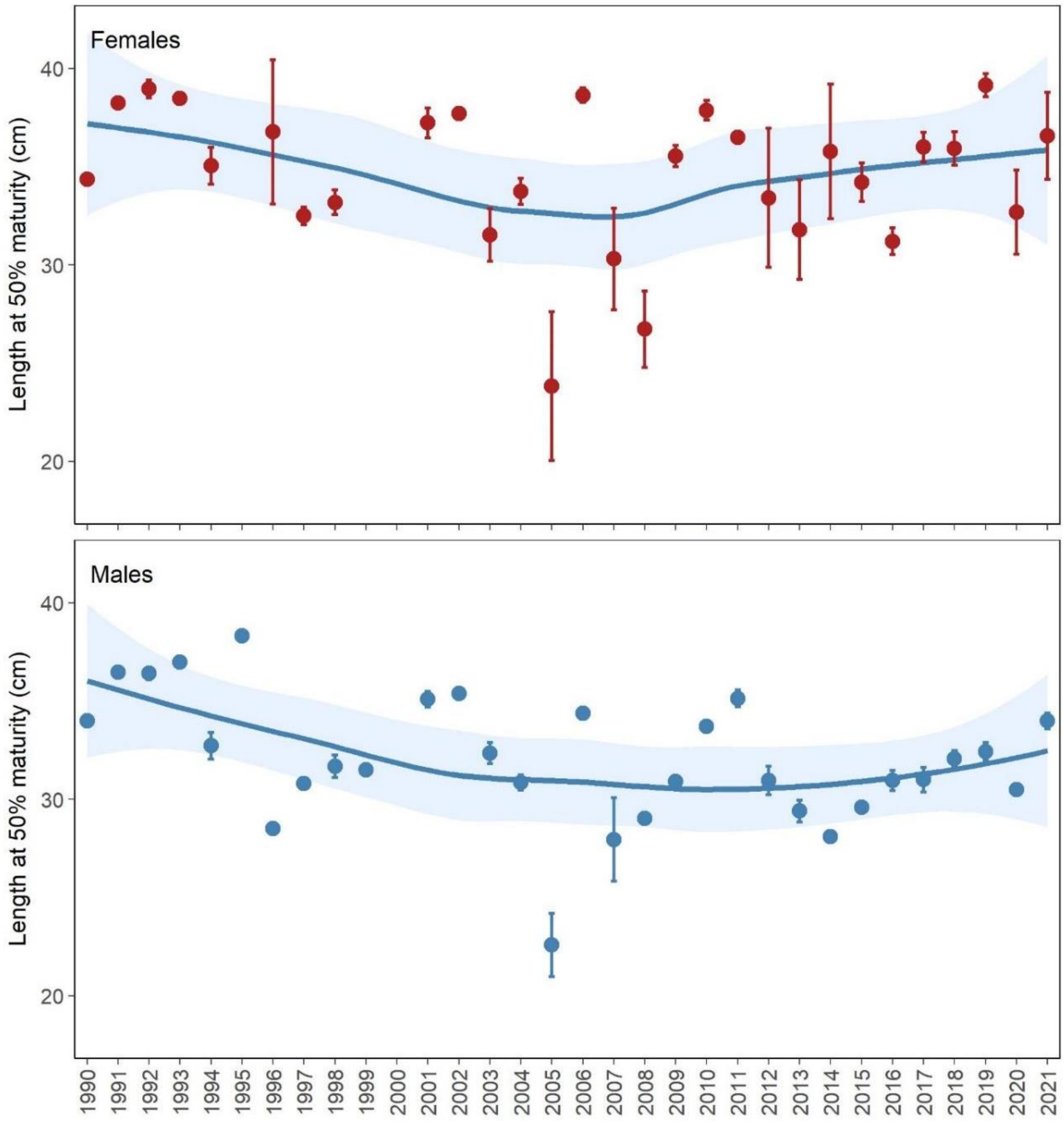

Fig. 5. Lengths at 50% maturity (L50) ± 1 standard error of female (red dots) and male (blue dots) southern blue whiting caught by finfish (A–, G–, and W–licences), experimental (E–licence), and surimi (S–licence) vessels in the FICZ throughout each year from 1990 to 2021, with LOESS smooths ± 95% confidence intervals (LOESS; span = 0.75, degree = 2).

3.3.3. Catch at length

Females (n = 92,743) ranged in size from 6 cm to 70 cm total length, and males (n = 107,445) ranged from 12 cm to 72 cm total length. Length-groups were not discernible due to size overlap most years. Individuals ≥ 45 cm total length were more common most years from 1990 to 2009. With large animals exiting the stock, smaller females and males (< 40 cm total length) became frequent in several years since 2010 (Fig. 6; Appendix VIII). The catch was mostly comprised of females and males at sizes ≥ L50 in 69% and in 84% of the total number of years assessed (n = 32), respectively (Fig. 6; Appendix VIII).

4. Conclusions

Length-based indicators suggest that MSY and optimal yield were positive most years since 1990; then MSY was negative some years since 2014, and optimal yield was of concern or negative some years since 2010 for females and since 2012 for males. However, surimi vessels that used to target this stock sporadically since 1999 stopped fishing activities in 2017 due to the declining catch trends observed since the early 2000s, and due to resulting high operative costs. For southern blue whiting, LBI are likely affected by the closure of the fishery in spawning grounds (which limits access to biological samples of spawning individuals and juveniles), and by the shift from a surimi fleet targeted fishery to a finfish bycatch fishery; LBI may thus be a reflection of the fisheries rather than a reflection of the stock itself.

Conservation of mega-spawners was positive most years from 1990 to 2016 but was negative or of concern in 2010, and most years from 2014 to 2018. However, fewer large spawners were caught since 2014, affecting the calculations of L_{Inf} and L_{Opt}, and thus affecting the assessment for mega-spawners. In contrast, conservation of large individuals was positive from 1990 to 2021. Positive conservation of mega-spawners and large individuals may be in part due to a no-fishing area for the surimi fleet that was implemented in 2010 to the south and southwest of the Falkland Islands from 1 July to 15 October to protect reproductive individuals (Falkland Islands Government 2021). Positive conservation of large individuals, and of mega-spawners for most years, is consistent with interannual patterns of asymptotic lengths and length at 50% maturity for both females and males.

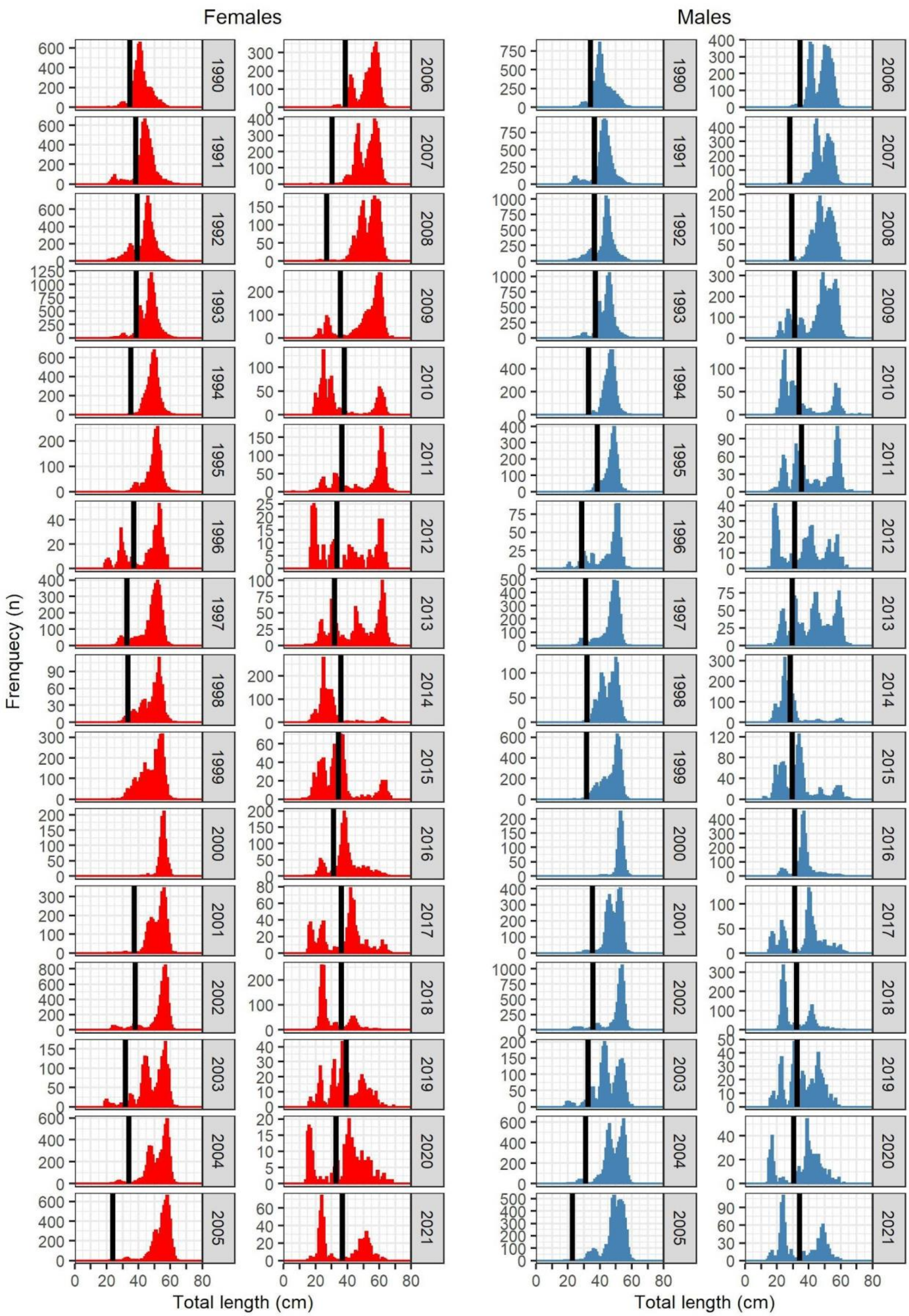

Fig. 6. Length frequency distribution of female and male southern blue whiting caught by finfish (A–, G–, and W–licences), surimi (S–licence), and experimental (E–licence) vessels in the FICZ from 1990 through 2021. The black solid lines indicate the length at 50% maturity (L50).

Length indicators for the conservation of immature individuals were mostly negative since 2009–2010 for both females and males. Accordingly, catch at length analysis showed that over the past decade high frequencies of small individuals were caught before reaching L50. Bycatch avoidance and discard of small individuals that have not reached maturity should be of high importance in Falkland Islands fisheries. On the other hand, length frequencies over the past 5 years showed the main peak at about 20 cm total length, and a secondary peak at about 40 cm total length, smaller than the modal length of 52 cm total length found during September 2022 by Arkhipkin et al. (2022), and smaller than the common commercial size observed during its abundant commercial fishery 20–25 years ago. This may be an indication that the number of juveniles is increasing in the FICZ.

The ICES category 5 Total Allowable Catch calculated for the Falkland Islands in 2023 (406 t) is 20% lower than the TAC set for 2022 (508 t; Ramos & Winter 2021), a decrease consistent with the Falkland Islands decreasing annual commercial catches in recent years.

Given the low catch of southern blue whiting in the Southwest Atlantic over the past decade, the precautionary ICES category 5 TAC for southern blue whiting in Falkland Islands waters was set at 406 t for 2023. Note that this ICES category 5 TAC corresponds to the expectation that in 2023, southern blue whiting will continue to be taken as trawl bycatch only. If a target fishery under S licence is renewed, it may be allocated a statutory TAC of 2,000 t and potentially additional catch in the format of an exploratory fishery (Falkland Islands Government 2022), as a recent survey has suggested a substantial biomass (Arkhipkin et al. 2022).

Patterns of L_{Inf} and L50, the presence of small individuals since 2009, and high densities of southern blue whiting at sizes near to commercial size in spawning grounds during the spawning season (Arkhipkin et al. 2022) suggest that the southern blue whiting stock is recovering slowly.

5. Recommendations

The ICES category 5 TAC calculated at 406 t for 2023, is based on the assumption that southern blue whiting will continue to be taken only as trawl bycatch during 2023. However, a statutory TAC of 2,000 t is maintained for S (surimi) licence, and may be augmented by an

FIFD-approved joint exploratory survey to estimate the southern blue whiting biomass fishable under commercial conditions (Falkland Islands Government 2022).

Conservation measures should be implemented, in particular for the conservation of immature individuals, by monitoring closely the bycatch and reporting of small and immature individuals.

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Appendix

Appendix I. An age-structured production model was implemented in CASAL (Bull et al. 2012) to calculate annual biomasses. The model was run including datasets from southern blue whiting commercial fisheries in the Falkland Islands and Argentina. CASAL requires one or more annual abundance indices to tune the estimation. Four CPUE time series (t/h) were available as indices of relative abundance between 1987 and 2016 from the Falkland Islands and Argentina. CPUE from the Falkland Islands Polish fleet (November to January) and surimi fleet (first and second halves of the year separately) were calculated from FIFD data. CPUE for the first half of the year of the Falkland Islands surimi fleet were calculated from January to June catch data, and for the second half of the year from November to December; these were modelled separately because the surimi fleet targets the feeding aggregations in the first part of the year, and the densely aggregated post-spawning aggregations in the second half of the year in Falkland Islands waters (Falkland Islands Government 2013).

The catch-at-age distributions for age classes 1 to 21+ years included the same four time series from the Falkland Islands and Argentina but with two fewer aggregate years of data in which catch-at-age information was not on record. Available age data from the FIFD were used to create a combined (male + female) age-length relationship that was used for the length frequencies of each year. Argentine catch-at-age proportions were estimated by deducting the Falkland Islands to Argentine catch proportion (Table 1 in Giussi et al. 2007) from the catch-at-age corresponding to both Falkland Islands and Argentine fisheries (Table 2 in Giussi et al. 2007). Catch per age class for each year and fishery were then expressed as catch proportions-at-age. For the catch-at-age data, effective sample sizes were estimated for each fishery and year combination to ensure that observations are given appropriate weights in the objective function (Francis 2011).

The model was set up as unsexed, single-area, and with a single annual time step; three annual time steps were also tested as per previous assessments (Falkland Islands Government 2013). Stock-recruitment was described as a Beverton-Holt relationship, with steepness parameter set to 0.75, a prior value derived from meta-analyses (Shertzer & Conn 2012). Steepness is defined as the fraction of recruitment from the unfished population when the spawning stock biomass declines to 20% of its unfished level (Mangel et al. 2013). The initial year in the model was set to 1987, the first year of southern blue whiting species data recorded by the FIFD. The current year in the model was set to 2021, the last year with catch data. Projections from the model extended for another 29 years, up to the year 2050. Conditions in the initial year were assumed to be equilibrium age structure at an unexploited equilibrium biomass. CASAL was run using two different natural mortality (M) estimates (Then et al. 2015): $M = 0.15$, $M = 0.21$. Deterministic MSY is the maximum equilibrium annual catch that CASAL optimization can achieve for the input parameters and specified catch split between the fisheries. For MSY calculations, recruitment for 2022–2050 was assumed to be log-normally distributed with sd = 0.6 as in previous assessments (Falkland Islands Government 2013). The future catch split was estimated from the 10-year (2012–2021) average of the southern blue whiting catch in each of the Falkland Islands and Argentina fleets.

For each run, CASAL produced B0, biomass, SSB, and MSY values from the Maximum Posterior Density (MPD) point estimates (Bull et al. 2012) with 95% confidence intervals defined by the 0.025 and 0.975 quantiles of Markov Chain Monte Carlo (MCMC) 10,000 iterations. The B0 estimate reached the upper bound in every run no matter how large this was set (i.e., 1,500,000 t; 2,500,000 t; 3,500,000 t; 4,500,000 t), which also resulted in increasing biomass and SSB estimates. Trace plots showed some convergence for biomass and spawning stock biomass but poor convergence for MSY.

Our model calculation was constrained for a number of reasons:

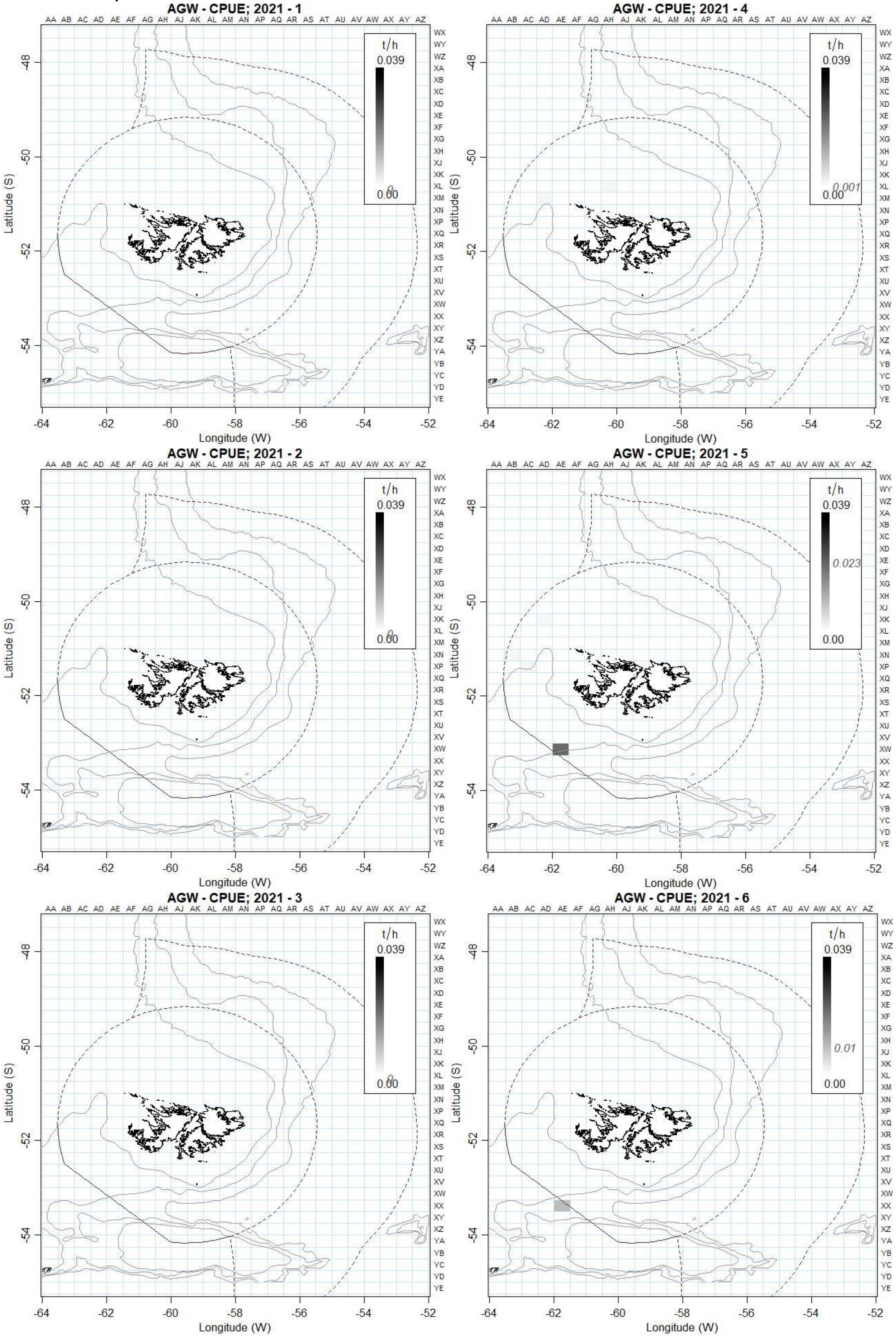
1) Some data used in previous FIFD stock assessments on southern blue whiting (Renewable Resources Assessment Group (RRAG) Virtual Population Analysis (VPA) 2004 (Falkland Islands Government 2009); CASAL (Falkland Islands Government 2010, 2011, 2012, 2013)) had to be discarded because their source could not be corroborated. With the updated data our results showed similar trends of biomass and SSB across years compared with those stock assessments; however, the magnitudes of annual biomass and SSB could not be replicated.
2) CPUE in the FICZ was calculated from FIFD data for years when southern blue whiting was targeted. However, no fishery has targeted this species in the FICZ since 2017 mainly due to conservation measures (Falkland Islands Government 2021). Therefore, reliable Falkland Islands abundance indices cannot be produced from CPUE for recent years, which limits our capacity to tune the model.
3) The FIFD has no access to Argentine abundance indices, other than those published several years ago and that are publicly available, e.g., Giussi & Wöhler (2007), and Giussi et al. (2007). Access to more recent INIDEP reports has been requested over the past four years but there has not been any response.
4) Future catch proportions of the different fisheries cannot be considered reliable in the absence of targeted fisheries since 2017 in the FICZ, as these may result in wider uncertainty for biomass projections.

Appendix II. Annual commercial catches (t) of southern blue whiting reported in Falkland Islands (excluding E–licence; Falkland Islands Government[4]; Falkland Islands Government 2021), Argentina (Government of Argentina[5]; Sánchez et al. 2012; Navarro et al. 2014, 2019) and Chile (Government of Chile[6]; SERNAPESCA 1990, 2000, 2011, 2021).

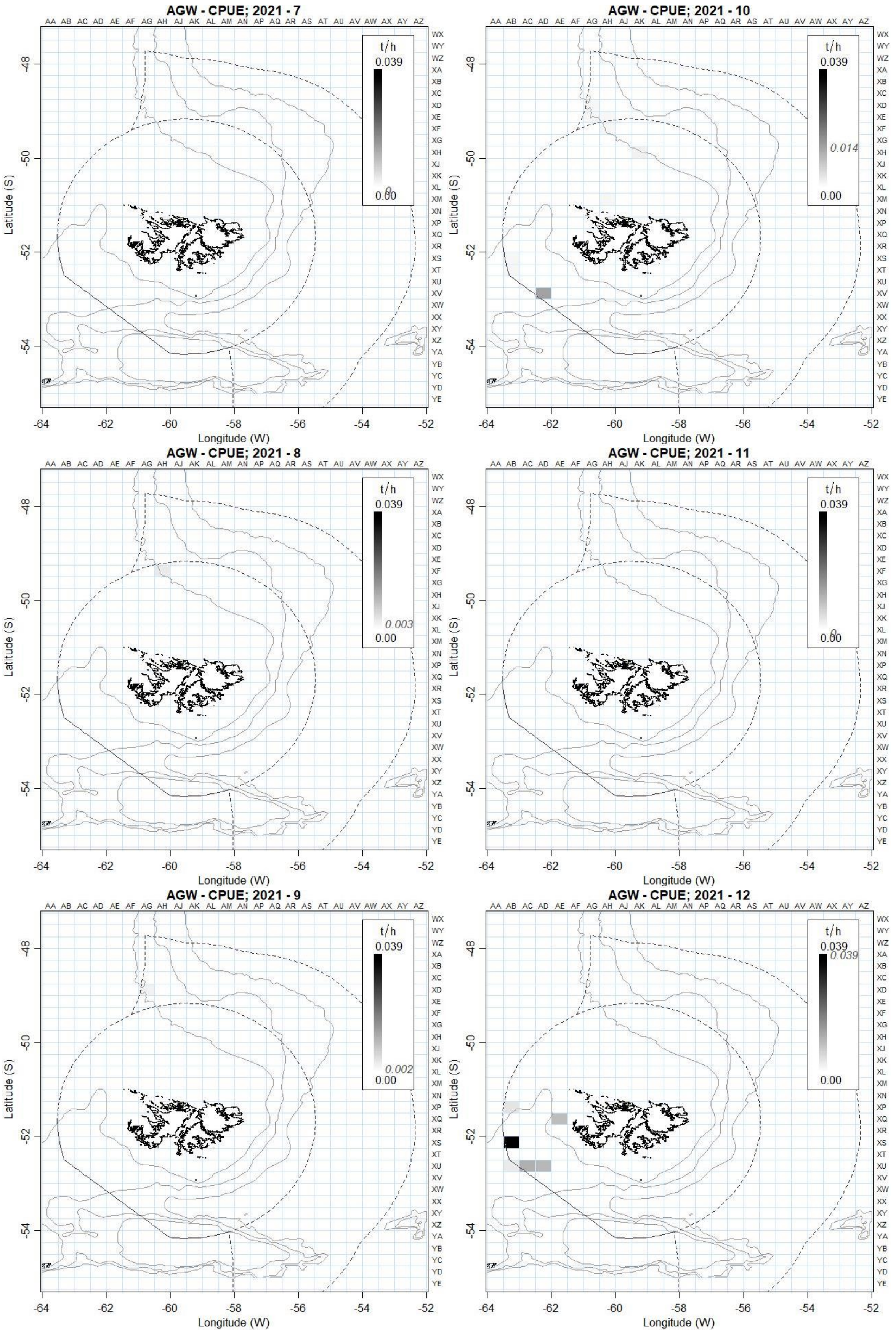
Year	Falkland Islands (t)	Argentina (t)	Chile (t)
1987	47,861.2	189.0	2,573.0
1988	48,678.0	1,307.0	4,710.0
1989	43,475.1	24,935.9	5,578.0
1990	71,876.2	32,844.9	3,931.0
1991	50,491.2	68,444.6	2,609.0
1992	34,078.4	90,095.1	5,149.0
1993	24,944.7	128,525.1	27,607.0
1994	38,677.9	91,048.3	4,664.0
1995	39,205.8	103,224.2	20,917.0
1996	23,741.8	84,624.5	25,445.0
1997	26,790.9	79,937.3	32,875.0
1998	31,473.8	71,626.1	40,857.0
1999	28,652.0	55,098.0	36,508.0
2000	23,370.7	61,313.1	27,459.0
2001	25,735.0	54,310.8	28,755.0
2002	24,908.1	42,453.3	29,409.0
2003	20,783.5	44,584.2	32,168.0
2004	28,550.9	50,215.8	33,169.0
2005	17,040.7	36,663.3	25,425.0
2006	20,378.6	31,292.2	29,115.0
2007	22,177.1	18,979.4	26,701.0
2008	13,239.8	19,841.1	27,086.0
2009	10,291.3	21,676.8	22,221.0
2010	6,448.1	11,628.0	23,301.0
2011	3,877.2	3,518.3	19,629.0
2012	1,576.0	8,378.8	16,675.0
2013	2,613.4	7,887.2	15,304.0
2014	3,527.1	9,050.3	11,191.0
2015	2,758.6	13,830.9	8,809.0
2016	5,330.0	13,235.9	8,269.0
2017	2,211.6	15,896.7	8,233.0
2018	962.1	11,288.9	5,199.5
2019	503.6	8,638.9	6,074.5
2020	58.0	8,897.3	3,899.0
2021	23.6	15,821.2	4,494.0

[4] http://www.fig.gov.fk/fisheries/publications/fishery-statistics
[5] https://www.agroindustria.gob.ar/sitio/areas/pesca_maritima/desembarques/
[6] http://www.sernapesca.cl/informes/estadisticas

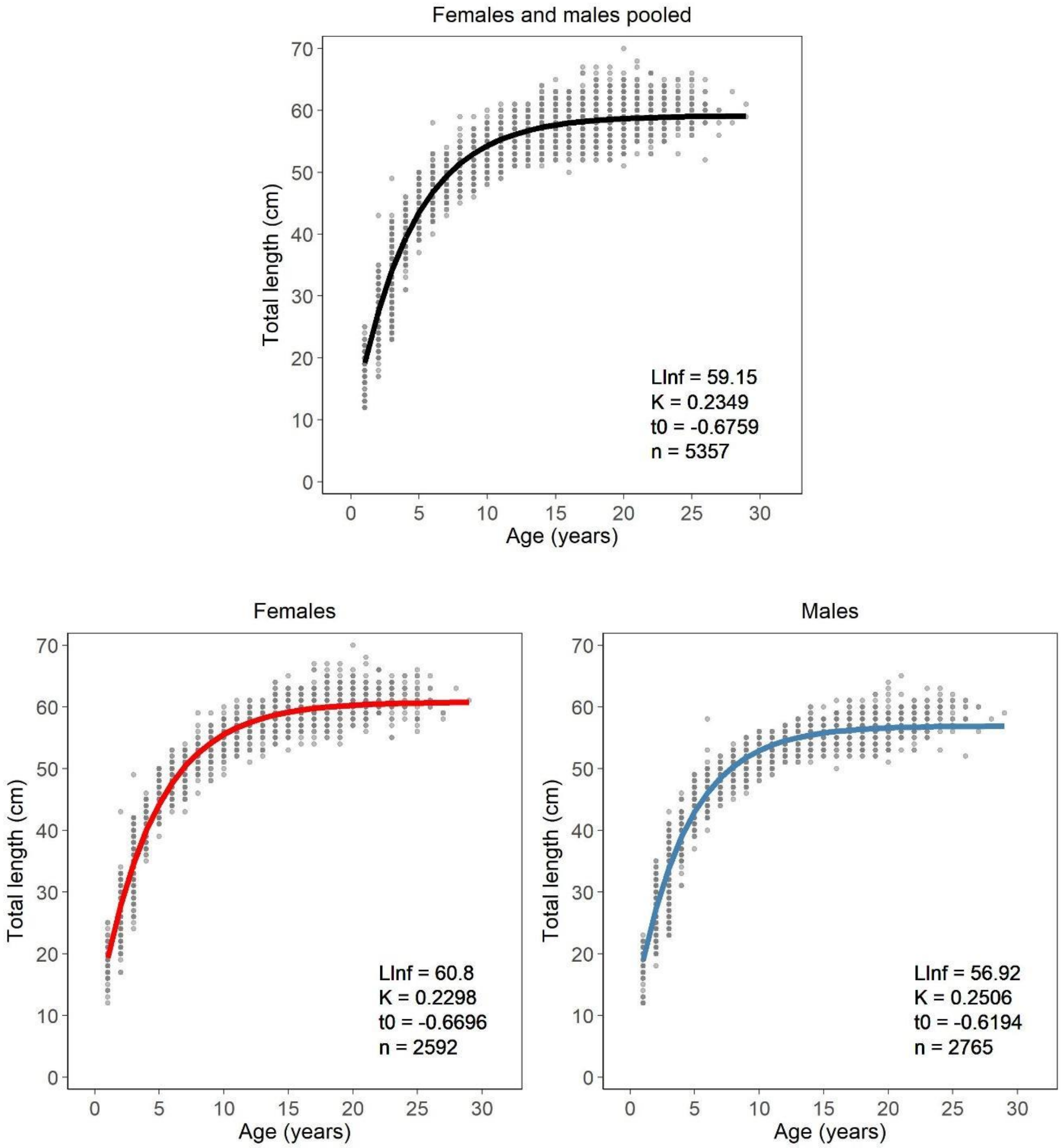
Appendix III. Monthly CPUE of southern blue whiting in Falkland Islands waters during 2021, calculated from finfish (A–, G–, and W–licences) vessels. There was no fishing effort during January and February under finfish licences.



Appendix III. *continued…*



Appendix IV. von Bertalanffy age-length relationship of female and male southern blue whiting sampled randomly and non-randomly in finfish (A–, G–, and W–licences), surimi (S–licence), and experimental (E–licence) vessels in the FICZ. Age was determined by MFRI (n = 5,356) and FIFD (n = 1) staff.

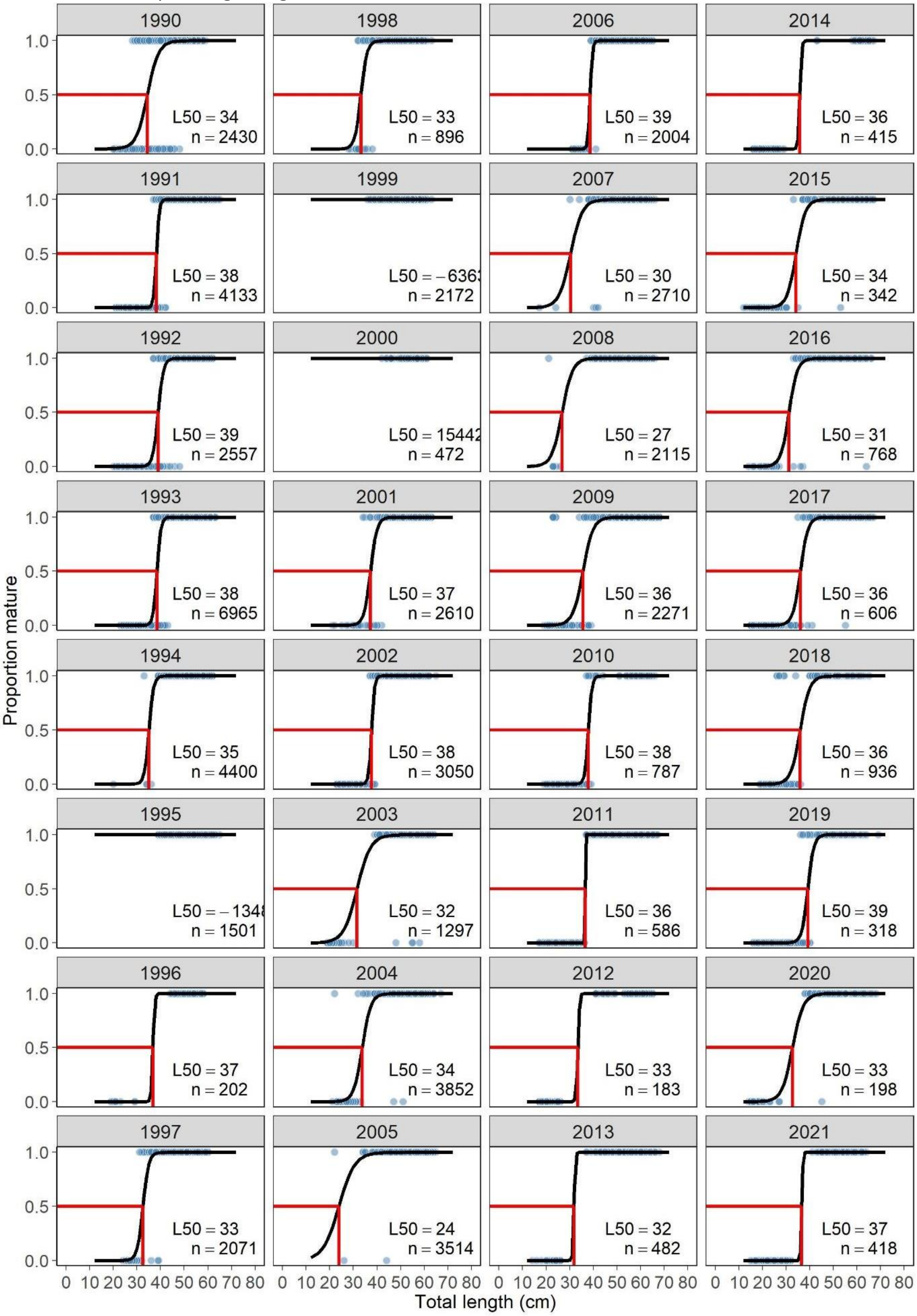


Appendix V. Southern blue whiting von Bertalanffy length-at-age parameters for curvature (k), age of fish at length zero (t_0), and asymptotic length (L_{Inf}), by year and sex, with 95% confidence intervals. Southern blue whiting were sampled randomly and non-randomly in finfish (A–, G–, and W–licences), surimi (S–licence), and experimental (E–licence) vessels in the FICZ.

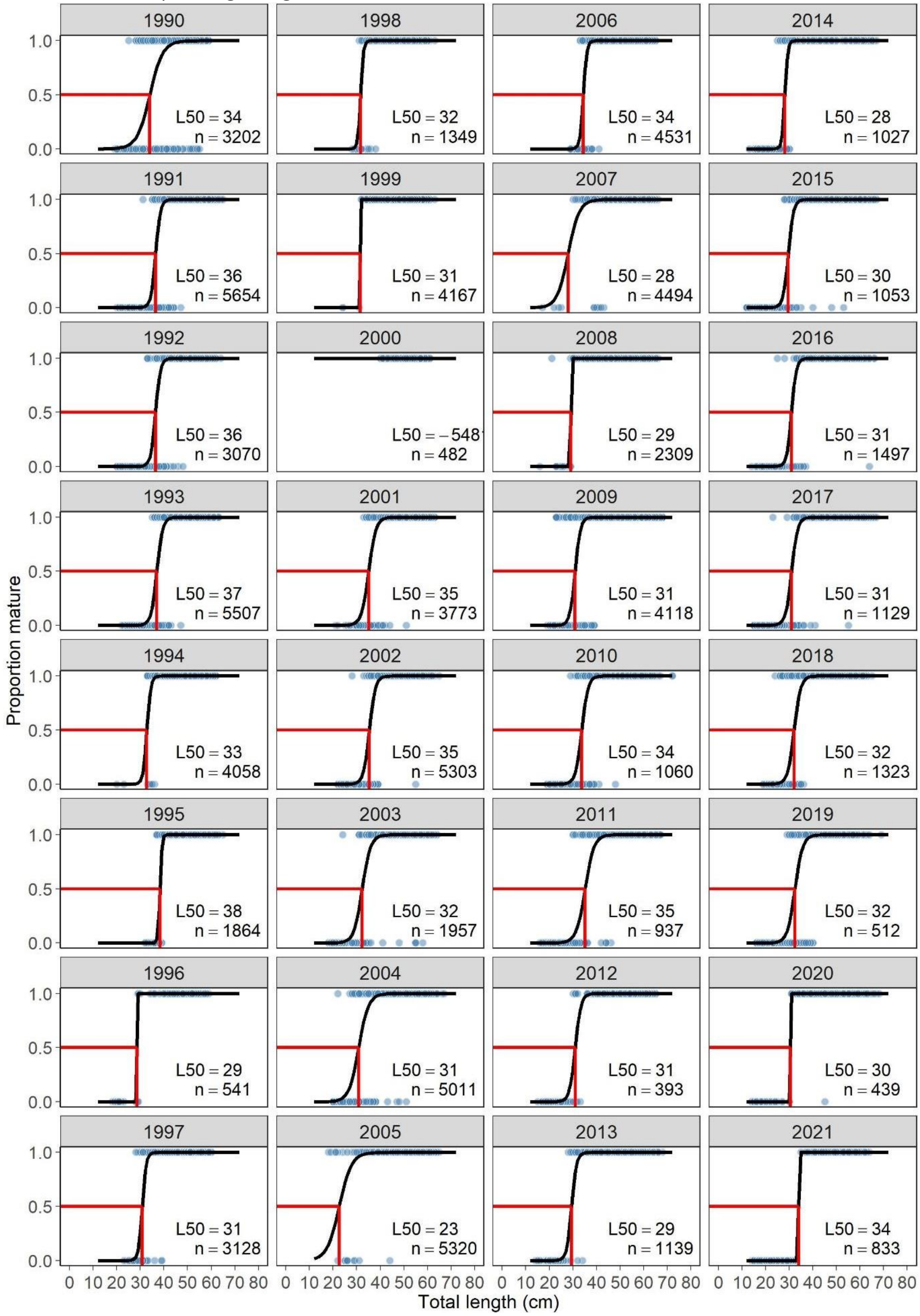
	Year	N	K		t_0 (years)		L_{Inf} (cm)	
	2002	114	0.276	(0.241 - 0.315)	-0.691	(-1.335 - -0.165)	58.086	(57.5 - 58.8)
	2003	10	0.213	(0.081 - 0.417)	-1.209	(-5.404 - 0.629)	61.118	(52.2 - 76.1)
	2004	408	0.206	(0.194 - 0.218)	-1.539	(-1.794 - -1.311)	60.495	(60.0 - 61.1)
	2005	171	0.291	(0.265 - 0.318)	0.046	(-0.338 - 0.363)	59.042	(58.5 - 59.6)
	2006	199	0.222	(0.203 - 0.243)	-1.000	(-1.373 - -0.667)	60.324	(59.6 - 61.2)
	2007	423	0.172	(0.159 - 0.186)	-2.205	(-2.644 - -1.812)	61.895	(61.2 - 62.7)
	2008	196	0.227	(0.207 - 0.248)	-0.845	(-1.284 - -0.470)	61.023	(60.4 - 61.7)
F	2009	145	0.251	(0.231 - 0.270)	0.097	(-0.309 - 0.411)	61.089	(60.5 - 61.7)
	2010	12	0.236	(0.113 - 0.493)	0.359	(-1.299 - 1.220)	62.200	(60.7 - 68.8)
	2011	24	0.192	(0.137 - 0.250)	-0.863	(-2.252 - -0.150)	63.328	(61.8 - 65.8)
	2012	36	0.227	(0.184 - 0.272)	-0.778	(-1.547 - -0.175)	61.853	(60.5 - 63.3)
	2013	71	0.237	(0.210 - 0.267)	-0.211	(-0.536 - 0.074)	62.742	(61.8 - 63.7)
	2014	221	0.213	(0.195 - 0.231)	-0.678	(-0.881 - -0.502)	63.398	(62.4 - 64.5)
	2015	267	0.235	(0.219 - 0.253)	-0.357	(-0.542 - -0.192)	62.716	(61.6 - 63.9)
	2016	174	0.215	(0.194 - 0.236)	-0.852	(-1.162 - -0.575)	61.641	(60.3 - 63.0)
	2017	8	NA	NA	NA	NA	NA	NA
	2018	113	0.254	(0.223 - 0.287)	-0.150	(-0.495 - 0.143)	61.516	(60.3 - 62.8)

	Year	N	K		t_0 (years)		L_{Inf} (cm)	
	2002	85	0.306	(0.255 - 0.363)	-0.707	(-1.527 - -0.055)	55.163	(54.4 - 56.0)
	2003	15	0.211	(0.025 - 0.561)	-0.654	(-4.725 - 1.313)	62.460	(49.4 - 206.3)
	2004	410	0.230	(0.216 - 0.243)	-1.257	(-1.487 - -1.043)	56.145	(55.6 - 56.7)
	2005	164	0.312	(0.286 - 0.340)	-0.318	(-0.614 - -0.048)	54.803	(54.2 - 55.4)
	2006	217	0.219	(0.196 - 0.243)	-1.650	(-2.096 - -1.273)	56.387	(55.4 - 57.5)
	2007	389	0.166	(0.152 - 0.182)	-3.344	(-3.889 - -2.843)	57.734	(57.0 - 58.5)
	2008	208	0.247	(0.228 - 0.266)	-1.043	(-1.354 - -0.755)	57.173	(56.6 - 57.8)
M	2009	192	0.248	(0.226 - 0.270)	-0.868	(-1.270 - -0.516)	57.146	(56.5 - 57.8)
	2010	6	NA	NA	NA	NA	NA	NA
	2011	24	0.242	(0.176 - 0.322)	-0.827	(-1.833 - -0.247)	59.000	(58.3 - 60.0)
	2012	35	0.199	(0.161 - 0.241)	-1.070	(-2.005 - -0.388)	59.809	(58.4 - 61.4)
	2013	83	0.211	(0.186 - 0.236)	-0.750	(-1.098 - -0.433)	59.705	(58.5 - 60.9)
	2014	236	0.224	(0.207 - 0.241)	-0.700	(-0.875 - -0.546)	59.386	(58.3 - 60.4)
	2015	358	0.237	(0.222 - 0.253)	-0.442	(-0.596 - -0.301)	58.392	(57.4 - 59.4)
	2016	199	0.210	(0.189 - 0.232)	-1.156	(-1.503 - -0.843)	58.512	(57.3 - 59.8)
	2017	8	NA	NA	NA	NA	NA	NA
	2018	136	0.245	(0.212 - 0.281)	0.043	(-0.393 - 0.414)	58.300	(57.1 - 59.6)

Appendix VI. Binomial logistic regressions of juvenile (0) or adult (1) maturity ogives vs. length for female southern blue whiting sampled randomly in finfish (A–, G–, and W–licences), surimi (S–licence), and experimental (E–licence) vessels in the FICZ. Red lines indicate the intercept for length at 50% adulthood, corresponding to Fig. 5.



Appendix VII. Binomial logistic regressions of juvenile (0) or adult (1) maturity ogives vs. length for male southern blue whiting sampled randomly in finfish (A–, G–, and W–licences), surimi (S–licence), and experimental (E–licence) vessels in the FICZ. Red lines indicate the intercept for length at 50% adulthood, corresponding to Fig. 5.



Appendix VIII. Number of southern blue whiting individuals sampled randomly for length frequency distributions in finfish (A–, G–, and W–licences), surimi (S–licence), and experimental (E–licence) vessels through the year in the FICZ from 2002 to 2021.

Year	Females (n)	Males (n)
2002	5,667	6,255
2003	1,939	2,304
2004	5,592	6,870
2005	5,825	6,025
2006	3,524	4,567
2007	4,620	4,553
2008	2,347	2,334
2009	3,137	4,677
2010	1,109	1,204
2011	1,359	1,268
2012	317	542
2013	1,256	1,574
2014	1,693	2,171
2015	951	1,417
2016	1,600	2,413
2017	811	1,250
2018	1,409	1,915
2019	553	662
2020	285	540
2021	542	905