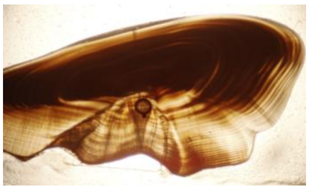
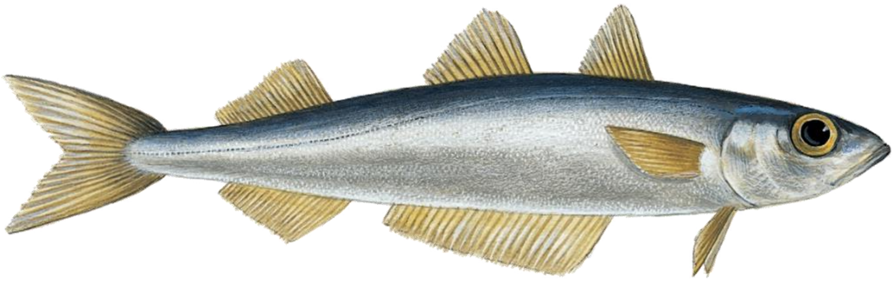
Stock Assessment of southern blue whiting (*Micromesistius australis australis*) in the Falkland Islands





SA - 2021 - BLU

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Natural Resources - Fisheries
Falkland Islands Government
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Summary

Commercial catches of southern blue whiting *Micromesistius australis australis* in Falkland Islands licenced fisheries were 58 tonnes in 2020, the lowest catch since 1990. Nearly 81% of commercial catches were by the restricted finfish W–licence. Recruitment pulses detected in 2005, 2010, 2011, 2012, 2014, 2017, and 2019 suggest that recruitment to the fishery occurs every 1 to 5 years.

Stock assessment of southern blue whiting was undertaken by the ICES category 5 advice rule for Total Allowable Catch, the Length-Based Indicator (LBI) method, and an age-structured production model in CASAL software. The ICES category 5 TAC was calculated at 508 tonnes, corresponding to the average of the last three years' catches. LBI suggested that conservation of large individuals and mega-spawners was mostly positive since 2002, consistent with positive trends in asymptotic lengths and stable yearly length at 50% maturity for both females and males. However, conservation of immature individuals has been poor since 2010, particularly for females. CASAL estimated an increase in biomass from 1987 to 1991, followed by a decrease to the lowest biomass in 2010 (446,038 t). The stock shows signs of slow recovery with biomass increasing gradually from 2011 to 2020 (617,757 t), and projections suggest further biomass increase (albeit wide confidence intervals) through the year 2050.

The multiple analyses used in this study suggest that the southern blue whiting stock is recovering slowly but is still in poor condition. ICES category 5 TAC was more conservative than CASAL TAC; therefore, ICES category 5 TAC was selected as the southern blue whiting TAC for 2022, set at 508 t for Falkland Islands fisheries.

1. Introduction

Southern blue whiting *Micromesistius australis 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.

2. Methods

Stock assessment of southern blue whiting was undertaken by three approaches in parallel: the ICES advice rules (ICES 2012, 2018) for Total Allowable Catch, the Length-Based Indicator (LBI) method (MEP 2020), and an age-structured production model in CASAL software (Bull et al. 2012). All three 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).

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 2020 (Falkland Islands Government on-line[a]; Falkland Islands Government 2021), Argentina (Government of Argentina on-line[b]; Sánchez et al. 2012; Navarro et al. 2014, 2019), and Chile (Government of Chile on-line[c]; SERNAPESCA 1990, 2000, 2011, 2021).

Commercial catches of southern blue whiting in Falkland Islands waters were examined by licence type to assess what licence caught the most in 2020. The spatial distribution of the 2020 monthly CPUE average was estimated from the finfish licence that contributed most of the southern blue whiting catches.

2.2. ICES Total Allowable Catch

In 2020, southern blue whiting was included in a Falkland Islands Government finfish stock assessment and management review (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 2021). 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. Little commercial fishery catch of southern blue whiting has been taken in the last five years, and would thus not serve as a

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

biomass index either. The alternative to category 3 is category 5, which consists of the average catches of the 3 previous years (MEP 2020):

$$TAC\_5_{2022} = \overline{C_{2018\ to\ 2020}}$$

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

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_∞ (Haddon 2001) and L50 (length at 50% maturity; Cope & Punt 2009).

LBI method was applied to all years from which observer length measurements of southern blue whiting were available and reported as random samples (FIFD database codes R and S), i.e., years 2002 to 2020. Total lengths of up to one hundred individuals per trawl were measured to the lowest centimetre. Because finfish trawls are restricted to larger meshes than calamari trawls, only observer length measurements taken in finfish-licensed 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; while skate and *Illex* currently do not have different mesh allowances from finfish, their different targets could also relate to characteristically different length-frequency distributions of southern blue whiting.

The procedure for identifying finfish-licensed observer samples is described in Appendix II. 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_∞ > 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). $L_{Opt} = 3 \cdot L_\infty \cdot (3 + Mk^{-1})^{-1}$ (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 $(3 \cdot L_C + L_\infty)/4$.

L_∞ and L50 parameters were assessed for females and males separately. Margins of variability of the six indicators were estimated by randomly re-sampling 30,000× on the normal distribution each year's fits of L_∞ and L50 to the LOESS smooths. Indicators were scored against the 'traffic light' scale (ICES 2015) with reference criteria >1 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, >0.8, and >0.3, yellow if 1, 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, <0.8, 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 for optimal yield was green if the lower and upper 95% quantiles spanned 1, yellow if the lower and upper 95% quantiles spanned 0.9 (the threshold used in ICES 2015) without spanning 1, and red otherwise. Reference criterion ≥1 for MSY was scored the same as >1, except that empirical values ≥1 were automatically green.

2.3.1. Length-age relationship

L_∞ was calculated from the von Bertalanffy growth function, modelled to southern blue whiting length and age data from the FIFD database with nonlinear least-squares fitting using the R package 'fishmethods' (Nelson 2019). Southern blue whiting length and age data were available for years 1988–2018, with status of age data advised 'with caution' (Lee et al. 2020) as verification of these ages is in progress. Variability of L_∞ and the other von Bertalanffy parameters was estimated by bootstrapping. Residuals of the von Bertalanffy model fit were randomly re-sampled with replacement, added back to the expected lengths; these newly generated data were re-fit to the von Bertalanffy function, and the 95% quantiles of 30,000 iterations retained as confidence intervals. Inter-annual trends of L_∞ were calculated by LOESS (span = 0.90, degree = 2, weighted by inverse variance), and the LOESS smooth fits were applied to mitigate unevenness over the time series.

2.3.2. Length at 50% maturity (L50)

Length at 50% maturity (L50) was calculated as the mid-point of the binomial logistic regression of maturity vs. length (Heino et al. 2002). Gonadal maturity is cyclical as fish pass through pre- to post-spawning phases, and definitive maturity assignments can only be made that stages 1 are immature and stages 3 or higher are mature (H. Randhawa, FIFD, personal communication). Therefore, maturity assignment was simplified to a dichotomous classification of juvenile (0 – 1) or adult (3+), omitting stage 2. The aggregates of L50 were plotted against years and trends calculated with LOESS smooths (span = 0.90, degree = 2), also weighted by inverse variance of each year's binomial logistic regression. The LOESS smooths of L50 were used as the yearly L50 values for LBI.

2.3.3. Length frequencies

Length frequencies were examined yearly for females and males to describe patterns in length. Lengths of individuals sampled randomly (FIFD database codes R and S) on finfish bottom and semi-pelagic commercial trawl vessels (i.e., A–, G–, S– and W– licences) and survey vessels (E– licence), were included in the analysis. Unsexed individuals were excluded.

2.4. Biomass estimates - CASAL

Biomasses were estimated using an age-structured production model implemented in CASAL (Bull et al. 2012). CASAL is a generalized age- or size-structured stock assessment software which can include structuring by sex, maturity or growth, and can cater for a number of fisheries, areas, stocks and information sources (Falkland Islands Government 2013). The model was run including datasets from southern blue whiting commercial fisheries in the Falkland Islands and Argentina. Commercial fisheries in Chile were not included due to the evident complex relationship between catches in the Southwest Atlantic (Falkland Islands + Argentina) and Southeast Pacific (Chile; Fig. 1).

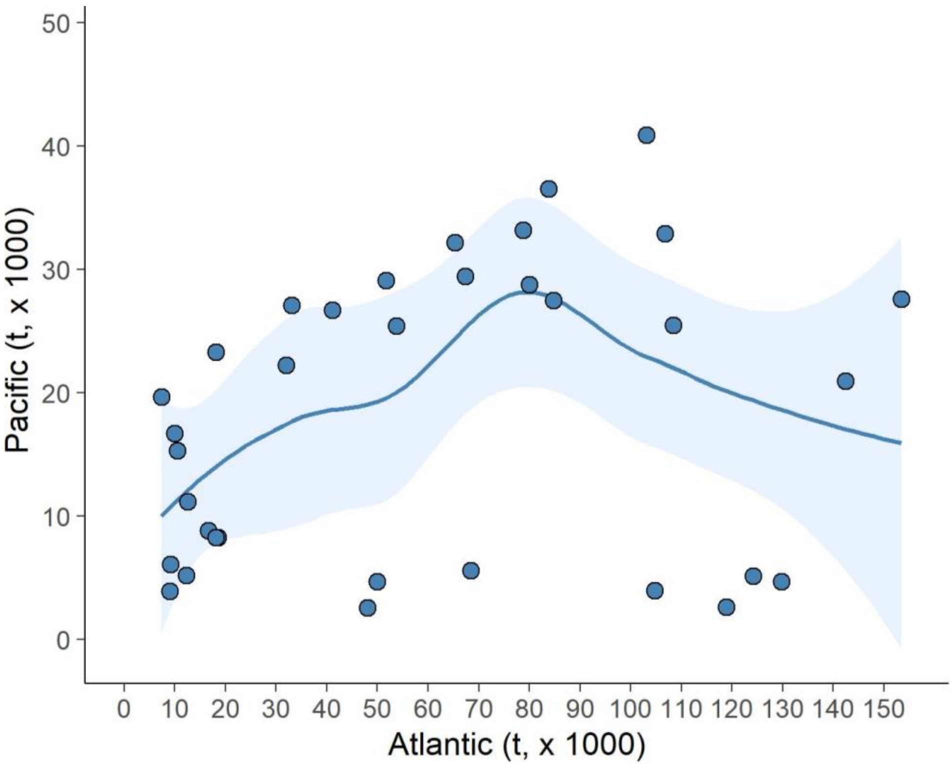

Fig. 1. Annual commercial catches of southern blue whiting, Atlantic (Falkland Islands + Argentina) vs. Pacific (Chile), from 1987 to 2020. Blue lines: LOESS (span = 0.75, degree = 2) smooths ± 95% confidence intervals.

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 (Appendix I). 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. While the Falkland Islands and Argentine fishing zones are broadly contiguous, connectivity with Chile is mediated through a narrow and oceanographically dynamic passage, and including Chilean catches in the model would accordingly risk inconsistent outcomes. Furthermore, peak biomasses of southern blue whiting in Chilean waters have been estimated in the range of 87,759 t – 199,975 t from 2001–2012 (Contreras et al. 2013), whereas spawning stock biomass alone was estimated in the range of 200,000 t – 500,000 t in the Southwest Atlantic over the same period of time (RRAG 2002). Commercial annual catches in the Southwest Atlantic have been 1–45× higher in 30 out of 34 years of the 1987 – 2020 time series than Southeast Pacific annual catches (Figs. 1–2). With the stock occurring predominantly in the Southwest Atlantic, CASAL modelling restricted to Falkland Islands and Argentine data (as in earlier assessments, RRAG 2002) may be considered reliable.

Annual biomasses were estimated since 1987, when systematic catch by species records were started in the Falkland Islands (Falkland Islands Government 1989). Observations and input parameters of each fishery are described in further detail in the following sections and are summarized in Table I. Observations are data which appear in the objective function and are used to fit the model (e.g., catch time series). Input parameters are estimated outside the model, and then treated as fixed parameters within the model (e.g., von Bertalanffy growth coefficients).

2.4.1. Abundance indices

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 (Table I). While several of these time series overlapped, they represented an aggregate total of 50 years of data. 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 April 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).

2.4.2. Catch at age

The catch-at-age distributions 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 (Table I). 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; however, data from 0 to 2 years old individuals were not included for the age-length relationship because of considerable variation in age determination of these age classes (H. Randhawa, FIFD, *pers. comm.*). Instead, the age-length relationship calculated with ages 3 and up was extrapolated back onto ages 0 to 2. Age estimates of 0 years were excluded from the analysis given these were only a few individuals. The age-length relationship then allowed calculating age for each individual caught and which length was measured, producing catch-at-age distributions for the Falkland Islands fisheries, from ages 1 to 25+. 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 effective sample sizes were estimated by a two-stage weighting approach. First, to address observation error, an effective sample size (N) of age-class data per year in each fishery was calculated based on data fit to the multinomial distribution using the function 'Neff.obs' in R package 'DataWeighting' (Francis 2013). Second, to address process error, effective sample sizes were multiplied by a weighting factor calculated as the inverse of the variance of difference between observed and expected mean age classes, standardized for the variance of the expected age distributions (Method TA1.8 in Table A.1 of Francis 2011). The two components of the objective function (50 years of relative annual abundance indices and 48 years of catch-at-age distributions) were then re-weighted to equalize. Accordingly, the effective sample sizes of the catch-at-age distributions were further multiplied by a factor of 50/48 = 1.041667.

2.4.3. Model setup

The model was setup as unsexed, single-area, and with a single annual time step. Recruitment to the population was calculated by multiplying average recruitment (R0) with estimated year class strength multipliers (YCS) and a stock-recruitment relationship. Stock-recruitment was described as a Beverton-Holt relationship, with a steepness parameter set to 0.75. 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 recorded data at the species level by the FIFD. The current year in the model was set to 2020, the last year with recorded catch data for the fisheries examined. Projections from the model extended for another 30 years, up to the year 2050. Conditions in the initial year were assumed to be equilibrium age structure at an unexploited equilibrium biomass.

Given the uncertainties in natural mortality (M) (Kenchington 2014), CASAL was run using four different M estimates (Gunderson et al. 2003; Zhang & Megrey 2006; Brodziak et al. 2011):

$$\mathrm{M} = \frac{4.3}{\mathrm{t_{max}}} \qquad \text{(Then et al. 2015)}$$

$\mathrm{M} = 4.899 \times \mathrm{t}_{\max}^{-0.916}$ (Then et al. 2015)

$\mathrm{M} = 4.118 \times \mathrm{k}^{0.73} \times \mathrm{L}_{\infty}^{-0.33}$ (Then et al. 2015)

$\mathrm{M} = 1.82 \times \mathrm{k}$ (Charnov et al. 2013)

where t_{max} = maximum age, L_{∞} = asymptotic length, and k = rate by which L_{∞} is approached; maximum age was taken from the Falkland Islands Fisheries Department (FIFD) age-length database.

Table I. Information used for the CASAL model. FK) Falkland Islands; AR) Argentina; FIFD) Falkland Islands Fisheries Department.

Data type	Data	Time series	Source
Observations	*CPUE*		
	FK Polish fleet	1987–1996	FIFD
	FK surimi fleet-First half of the year	2000–2006, 2009–2012, 2016	FIFD
	FK surimi fleet-Second half of the year	1999–2002, 2004–2011, 2014	FIFD
	AR surimi fleet	1992–2006	Giussi & Wöhler (2007); Giussi et al. (2007)
	Catch-at age		
	FK Polish fleet	1988–1996	FIFD
	FK surimi fleet-First half of the year	2001–2004, 2009–2010,2016	FIFD
	FK surimi fleet-Second half of the year	1999–2000, 2002, 2004–2011, 2014	FIFD
	AR surimi fleet	1987–2006	Giussi et al. (2007)
Input parameters	*Length-weight*		
	FK	All available data	FIFD
	Natural mortality		
	FK	All available data	FIFD
	Maturity-at-age		
	FK	All available data	FIFD
	FK-AR		Giussi et al. (2007)

2.4.4. Estimation method

Model parameters were estimated by minimising the sum of the negative log-likelihoods from the observations, negative-log Bayesian priors, and penalties that constrain the parameterisations. The parameter values presented in the report are the Maximum Posterior Density (MPD) point estimates (Bull et al. 2012).

Markov Chain Monte Carlo (MCMC) was used to estimate the joint posterior distribution of the parameters in a Bayesian analysis. The starting point of each chain was set to the corresponding MPD. Burn-in was set to 100,000 iterations, and every 100th value was taken from the next 1,000,000 iterations. The resulting 10,000 values represent a systematic sample from the Bayesian posterior distribution for the parameter of interest. The parameters estimated by the model, their priors, starting values and bounds are provided in Table II.

Table II. Parameters estimated by CASAL. N) Numbers; SSB_0) Non-exploited Stock Biomass; YCS) Year Class Strength.

Parameter	N	Prior	Start value	Lower bound	Upper bound
SSB_0	1	uniform-log	1,000,000	800,000	†,*
YCS	33	lognormal	1	0.001	10–20
Selectivity SBW1		uniform			
a_{50}	1		5	1	50
a_{to95}	1		6	0.05	50
Selectivity SBW2		uniform			
a_{50}	1		7	1	50
a_{to95}	1		11	0.05	50
Selectivity SBW3		uniform			
a_{50}	1		7	1	50
a_{to95}	1		10	0.05	50
Selectivity SBW4		uniform			
a_{50}	1		5	1	50
a_{to95}	1		12	0.05	50
q SBW1	1	uniform-log	-	$1x10^{-8}$	0.1
q SBW2	1	uniform-log	-	$1x10^{-8}$	0.1
q SBW3	1	uniform-log	-	$1x10^{-8}$	0.1
q SBW4	1	uniform-log	-	$1x10^{-8}$	0.1

SBW1) Falkland Islands Polish fleet; SBW2) Falkland Islands surimi fleet first half of the year; SBW3) Falkland Islands surimi fleet second half of the year; SBW4) Argentina surimi fleet. YCS consists of 33 parameters (for years 1986–2018) and values in the table apply to each of them. †For natural mortality M = 0.15 and M = 0.23, upper bounds for initialization of B_0 were set at 1,500,000. *For M = 0.33 and M = 0.36, upper bounds for initialization of B_0 were set at 3,500,000.

The pre-exploitation equilibrium spawning stock biomass (SSB_0) is the spawning stock biomass that would exist with average recruitment in the absence of fishing. A uniform-log prior was used for the estimation of SSB_0. Catchability coefficients (q) were estimated for the different CPUE series separately and treated as 'nuisance' parameters (default in CASAL); therefore, no starting values were provided. Selectivity-at-age was estimated using a logistic ogive separately for each Falkland Islands fishery (Polish fleet and surimi fleets). The logistic ogive is defined by two parameters: a_{50} (age at 50% selectivity) and a_{to95} (difference in age at 50% and 95% selectivity), where the value of selectivity at age x is given by:

$$f(x) = 1/[1 + 19^{(a_{50}-x)/a_{to95}}]$$

An approximate logistic ogive for Argentina was taken from Giussi et al. (2007).

2.4.5. MSY calculations

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 the MSY calculations, recruitment for 2019–2050 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 (2011–2020) average of the southern blue whiting catch in each of the Falkland Islands (Polish = 0 t; surimi first half = 20 t; and surimi second half of the year = 328 t) and Argentina (surimi = 9,400 t) fleets.

2.4.6 CASAL Total Allowable Catch (TAC)

The CASAL model, including Falkland Islands and Argentine data, obtains combined biomass and MSY estimates of both countries. MSY was referenced as the limit for TAC in accordance with common international standards (Hilborn 2007; Martell & Froese 2013). Falkland Islands TAC would then be calculated as a fraction of the combined MSY, and the relevant fraction based on historical catch, which is often used to estimate quota allocation on international and regional scales (Lynham 2014). Partition of the TAC for the Falkland Islands may thus be considered among the following options:

1) 10–, 5–, and 3–year average contributions (%) of the Falkland Islands relative to the combined catch of southern blue whiting in Falkland Islands and Argentina.

2) Equal share of the total catch limit of southern blue whiting between the Falkland Islands and Argentina, i.e. 50% each.

3. Results

3.1. Commercial fishery data

Southern blue whiting catches in Falkland Islands waters have represented approximately 35% 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 2020 (58 t). Combined catches across nations increased from 1987 through 1993, and declined towards 2010. Catches were relatively low but stable from 2011 through 2020 (annual average of 22,732 t; Fig. 2).

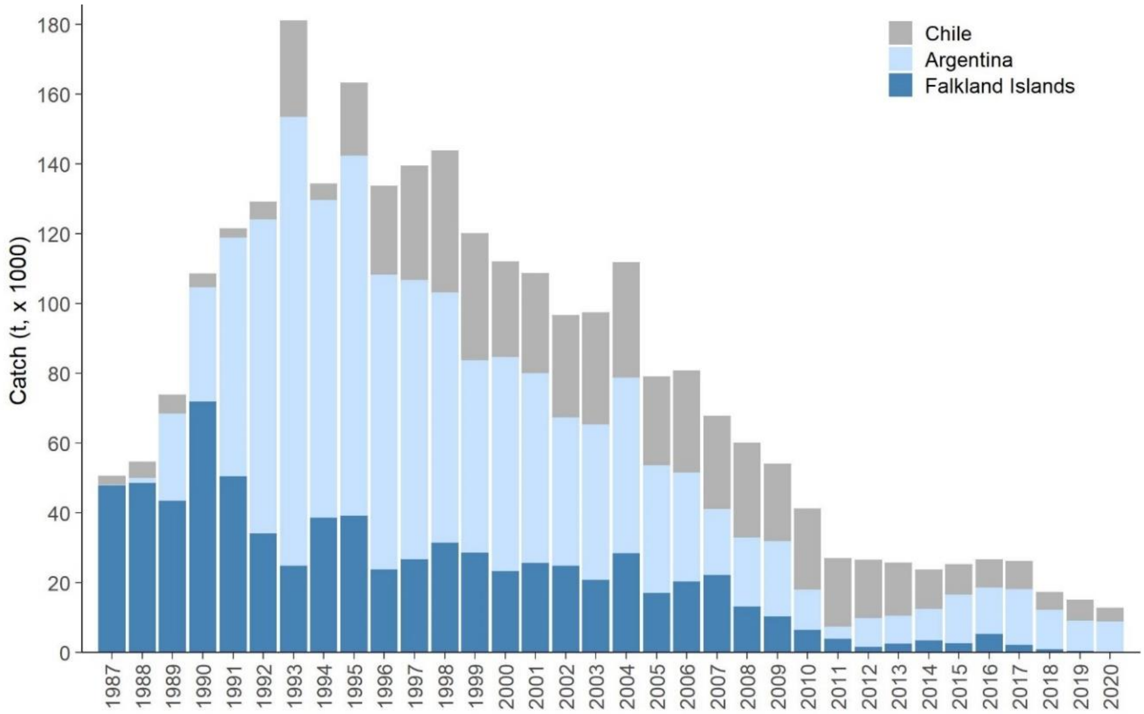

Fig. 2. Annual commercial catch of southern blue whiting in Falkland Islands, Argentine and Chilean waters. Falkland Islands commercial catch data exclude experimental (E–licence) and out-of-zone (O–licence) licences.

During 2020 a total of 68 t of southern blue whiting were reported caught in Falkland Islands waters, of which 57.9 t were reported under commercial licences, i.e., excluding the experimental E–licence. The restricted finfish W–licence accounted for 81% of the total southern blue whiting catch (Table III); most catches occurred to the southwest during January, February, and October (Appendix III).

Table III. Catches by licence of southern blue whiting in Falkland Islands waters during 2020.

Licence	Target species	Catch (t)	Catch (%)
W	Restricted finfish	55.38	80.52
E	Experimental	10.81	15.71
X	Calamari 2nd season	2.34	3.40
A	Unrestricted finfish	0.19	0.29
G	Restricted finfish and *Illex*	0.00	0.00
F	Skates and rays	0.00	0.00
C	Calamari 1st season	0.05	0.07
B	*Illex* squid	0.00	0.00
L	Toothfish (longline)	0.00	0.00
S	Southern blue whiting and hoki	0.00	0.00
O	Outside Falkland Islands waters	0.00	0.00
Total		68.77	100.00

3.2. ICES Total Allowable Catch

TAC for the year 2022 under the ICES category 5 assessment framework was estimated at 508 t:

$$TAC\_5_{2022} = \overline{962 + 504 + 58} = 508$$

3.3. Length Based Indicators

Yearly 'traffic light' length indicators for females and males are summarized in Tables IV and V, respectively. Indicator $L_C/L50$, for conservation of immature fish, was positive (green) from 2002 to 2009; however, it was mostly negative (red) from 2010 to 2020 for females and males. Conservation of immature males ($L_C/L50$) was positive in 2020. Indicator $L_{25\%}/L50$, also for conservation of immature fish, had positive outcomes (green) for females and males from 2002 to 2009; however, negative outcomes or of concern (yellow) were common since 2010 for both females and males. Indicator $L_{max5\%}/L_\infty$, for the conservation of large individuals, was positive from 2002 to 2020 for both females and males. Indicator P_{mega}, for the presence of mega-spawners, was positive from 2002 to 2013, and negative or of concern from 2014 to 2020 for both females and males. Indicator L_{meanC}/L_{Opt}, for optimal yield, was positive from 2002 to 2013, and fluctuated between negative, of concern, and positive from 2014 to 2020, with 2020 being positive for both females and males. Indicator $L_{meanC}/L_{F=M}$, for maximum sustainable yield, was positive from 2002 to 2013 for females and from 2002 to 2015 for males; there were fluctuations between negative, of concern and positive outcomes since 2014 for females and since 2016 for males, with positive outcomes in 2019 and 2020 for both females and males.

Table IV. Female southern blue whiting indicators by 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_∞) 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.

Ref.	Conservation				Optimal yield	MSY
	L_C / L50 >1	$L_{25\%}$ / L50 >1	$L_{max5\%}$ / L_∞ >0.8	P_{mega} >0.3	L_{meanC} / L_{Opt} ≈1	L_{meanC} / $L_{F=M}$ ≥1
2002	1.70	1.54	1.02	0.80	1.45	1.03
2003	1.25	1.28	1.02	0.81	1.32	1.10
2004	1.30	1.33	1.02	0.93	1.38	1.09
2005	1.47	1.39	1.03	0.97	1.45	1.03
2006	1.37	1.32	1.03	0.82	1.42	1.05
2007	1.19	1.24	1.02	0.92	1.33	1.10
2008	1.30	1.33	1.02	0.93	1.35	1.07
2009	1.43	1.40	1.04	0.85	1.41	1.07
2010	0.72	0.86	1.03	0.53	1.10	1.35
2011	1.88	1.28	1.05	0.60	1.50	1.03
2012	0.60	0.96	1.03	0.42	1.01	1.44
2013	2.05	1.09	1.06	0.58	1.51	1.03
2014	0.86	0.86	1.00	0.16	0.82	0.99
2015	0.81	0.87	1.03	0.12	0.89	1.10
2016	1.19	1.16	0.96	0.19	1.03	0.99
2017	0.48	0.72	1.01	0.23	0.90	1.36
2018	0.64	0.67	0.84	0.07	0.74	0.94
2019	0.58	0.81	0.95	0.28	0.95	1.21
2020	0.34	0.77	1.03	0.32	0.97	1.51

Table V. Male southern blue whiting indicators by 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_∞) 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

Ref.	Conservation				Optimal yield	MSY
	L_C / L50	$L_{25\%}$ / L50	$L_{max5\%}$ / L_∞	P_{mega}	L_{meanC} / L_{Opt}	L_{meanC} / $L_{F=M}$
	>1	>1	>0.8	>0.3	≈1	≥1
2002	1.54	1.33	1.04	0.79	1.48	1.02
2003	1.23	1.26	1.03	0.84	1.32	1.09
2004	1.33	1.36	1.04	0.93	1.37	1.08
2005	1.44	1.44	1.04	0.90	1.40	1.06
2006	1.24	1.30	1.02	0.80	1.30	1.11
2007	1.37	1.40	1.02	0.93	1.33	1.06
2008	1.45	1.45	1.02	0.93	1.35	1.05
2009	1.49	1.43	1.05	0.79	1.40	1.07
2010	0.77	0.99	1.04	0.54	1.13	1.34
2011	1.16	1.19	1.04	0.49	1.23	1.14
2012	0.59	0.92	1.03	0.35	0.99	1.37
2013	0.77	1.00	1.06	0.51	1.11	1.36
2014	0.81	0.85	1.00	0.20	0.87	1.04
2015	0.64	0.81	1.04	0.13	0.85	1.15
2016	1.22	1.18	0.94	0.12	1.01	0.95
2017	1.31	0.84	1.02	0.25	1.14	1.02
2018	0.76	0.80	0.89	0.10	0.81	1.00
2019	0.72	0.98	0.91	0.30	0.95	1.19
2020	1.25	1.06	0.96	0.25	1.13	1.01

3.3.1. Length-age relationship

Length and age of females (n = 5,222) ranged from 14 cm to 70 cm, and from 1 year to 27 years. The length-age relationship of females gave: L_∞ = 60.89 cm, k = 0.1892, and t_0 = -1.5408 years. Length and age of males (n = 5,103) ranged from 15 cm to 64 cm and from 1 year to 28 years, respectively. The length-age relationship of males gave: L_∞ = 56.60 cm, k = 0.2133, and t_0 = -1.4083 years (Appendix IV). Yearly von Bertalanffy parameters are summarized in Appendix V. Asymptotic lengths (L_∞) increased significantly from 1999 to 2016 for females, and from 1999 to 2018 for males (Fig. 3).

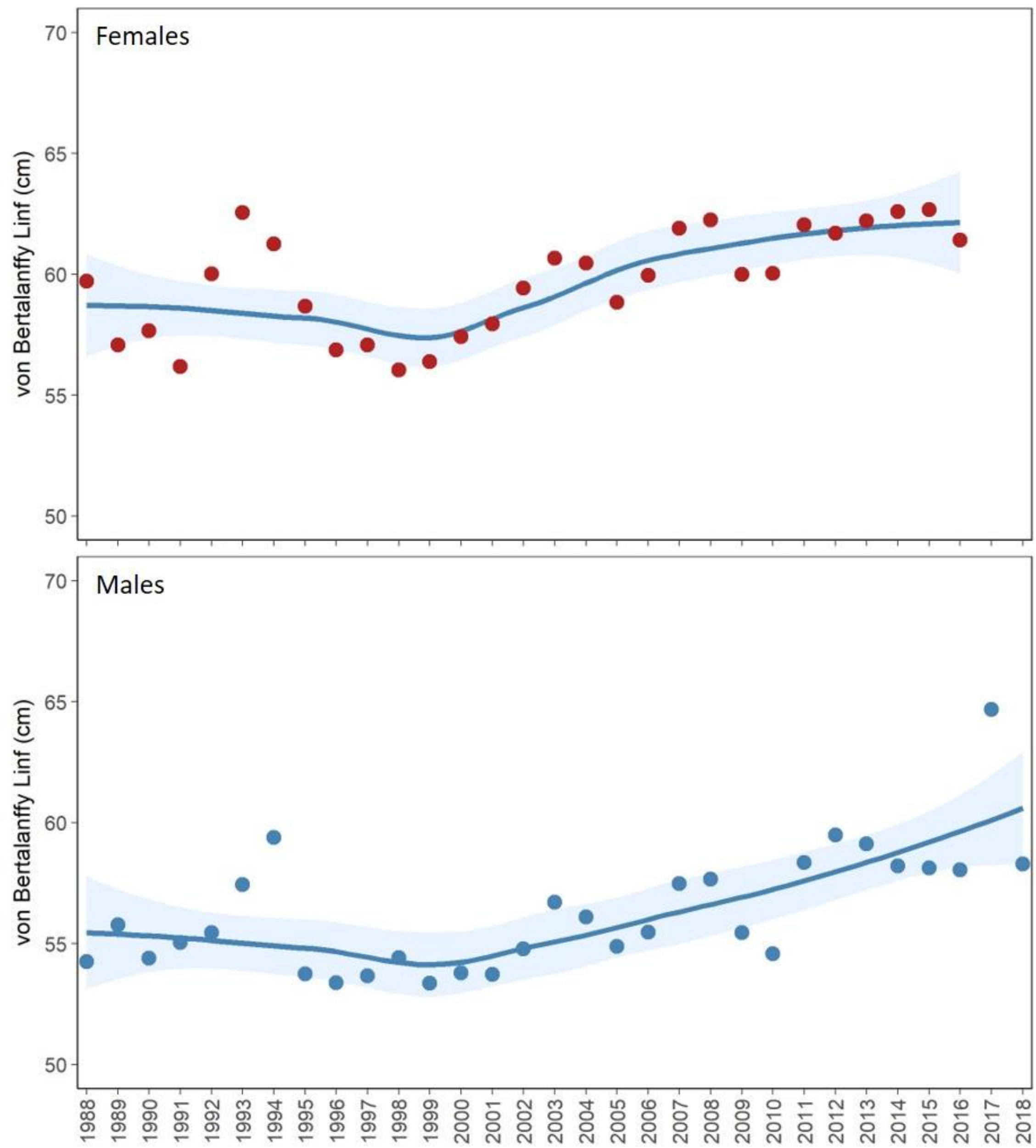

Fig. 3. Asymptotic lengths (L_∞) calculated according to the von Bertalanffy growth function for female and male southern blue whiting, 1988 to 2018. Blue lines and shaded area are LOESS smooths ± 95% confidence intervals.

3.3.2. Length at 50% maturity (L50)

Lengths at 50% maturity had no statistically significant change through time for females and males; length at maturity of females ranged between 24 cm and 39 cm for females, and between 22 cm and 35 cm for males (Fig. 4).

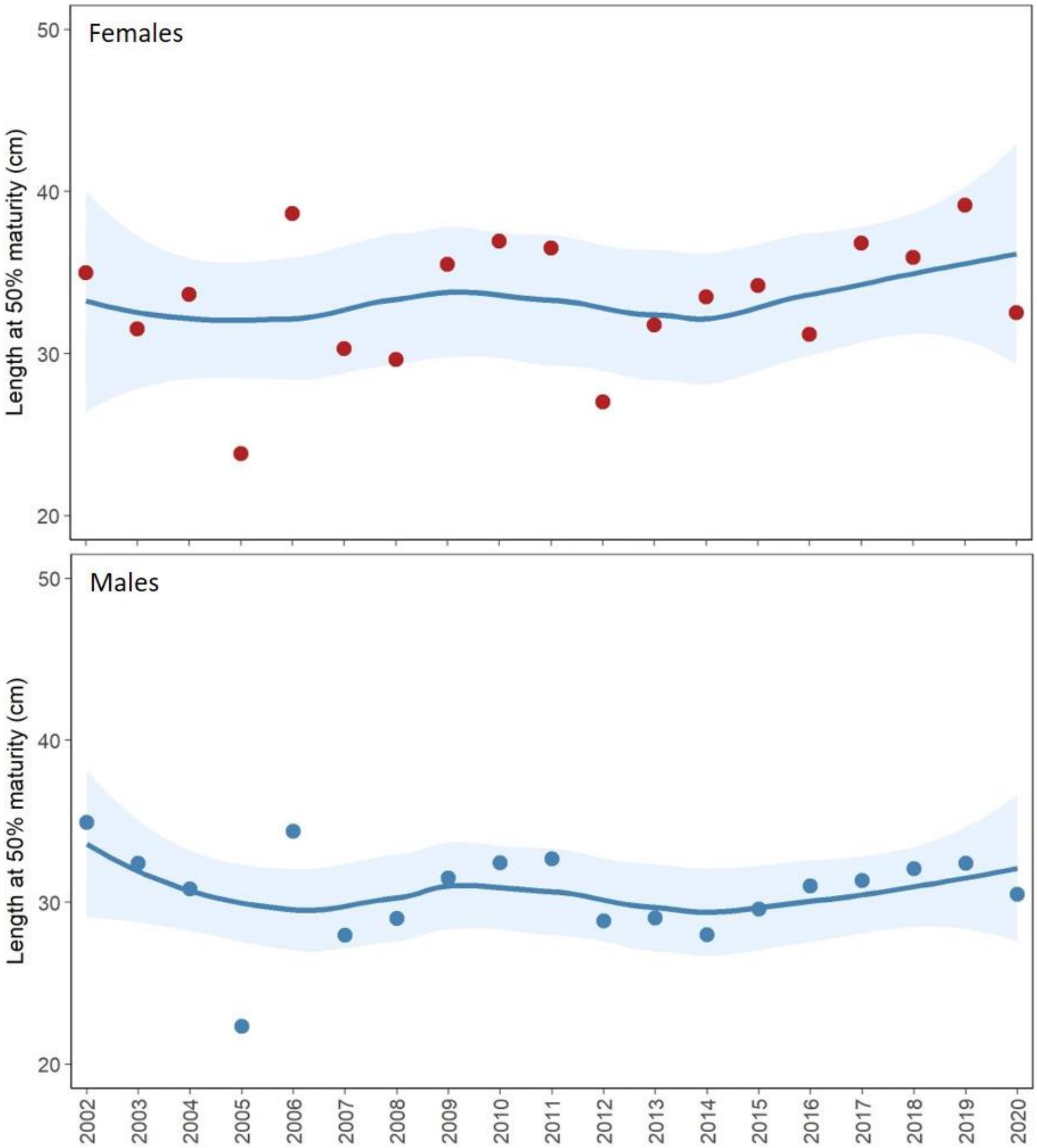

Fig. 4. Lengths at 50% maturity (L50) of female and male southern blue whiting, 2002 to 2020. Blue lines and shaded areas are LOESS smooths ± 95% confidence intervals. Yearly data correspond to the 0.5 length intercepts in Appendix VI.

3.3.3. Length frequencies

Females southern blue whiting were in the range of sizes from 6 cm to 70 cm total length, and males ranged from 12 cm to 72 cm total length. Females and males were characterized by several cohorts that were not discernible due to size overlap. Greater numbers of large individuals (≥ 50 cm total length or 7+ years old) were more common from 2002 to 2013 for females. Males ≥ 50 cm total length or 7+ years old were also frequent but not as dominant from 2002 to 2013, with other cohorts at ≤ 40 cm total length or ≤ 4 years old being equally frequent in some years. With large cohorts exiting the stock, a shift to smaller females and males (< 40 cm total length or ≤ 4 years old) seems to occur from 2012 to 2020. Recruitment pulses detected in 2005, 2010, 2011, 2012, 2014, 2017, and 2019 suggest that recruitment to the fishery of 1 to 5 years old individuals occurs every 1 to 5 years (Fig. 5; Appendix VII).

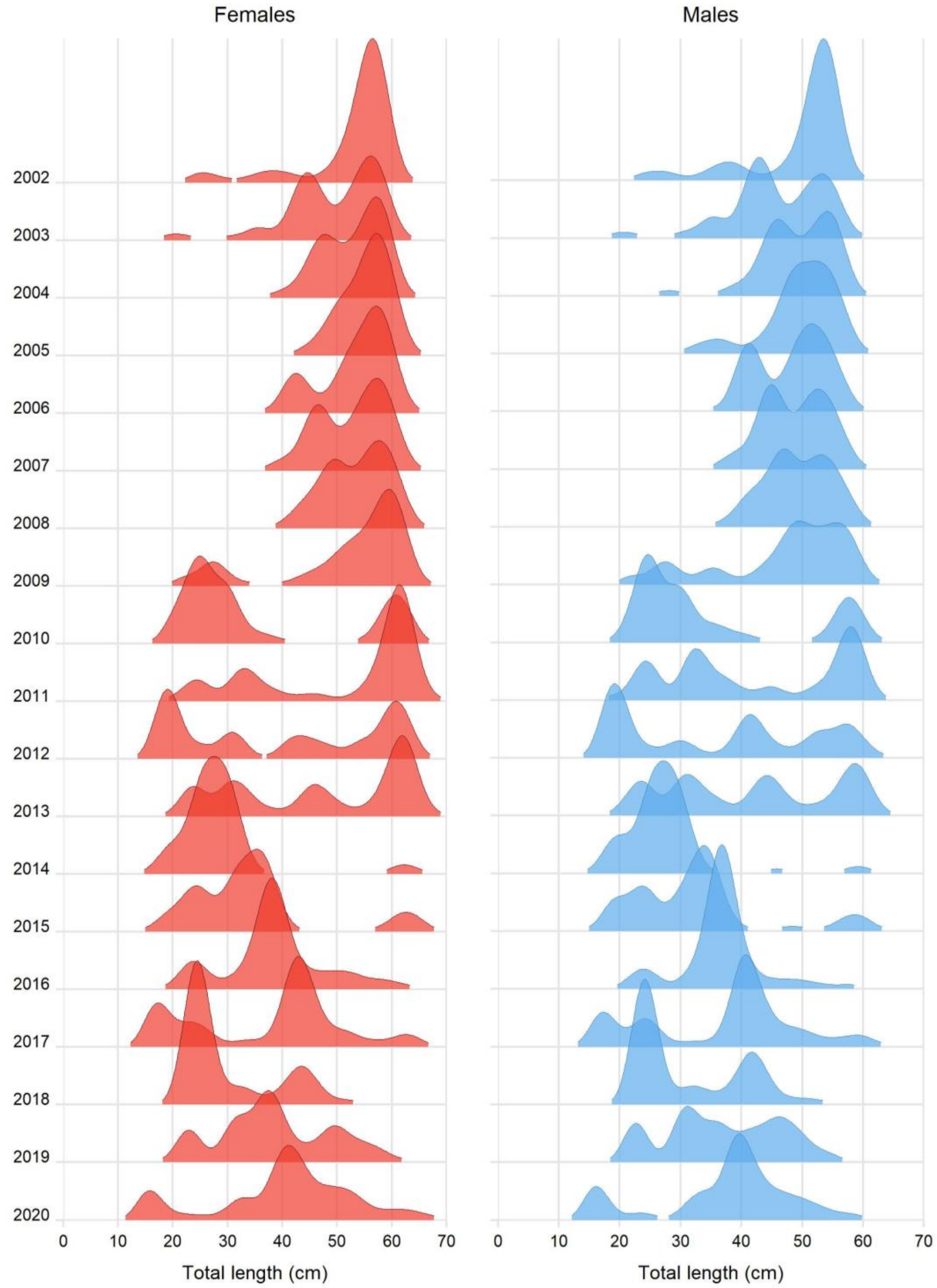

Fig. 5. Length frequency distribution of female and male southern blue whiting in Falkland Islands waters.

3.4. Biomass estimates - CASAL

3.4.1. Observations and parameters

CPUE of the Polish fleet in Falkland Islands waters ranged between 2,102 kg/h and 4,117 kg/h from 1987 to 1996. CPUE of the surimi fleet was relatively lower during the first half of the year (1,029 – 6,807 kg/h) compared with the surimi fleet during the second half of the year (4,308 – 13,273 kg/h) in Falkland Islands waters. In Argentina, CPUE ranged between 1,022 kg/h and 4,883 kg/h (Fig. 6).

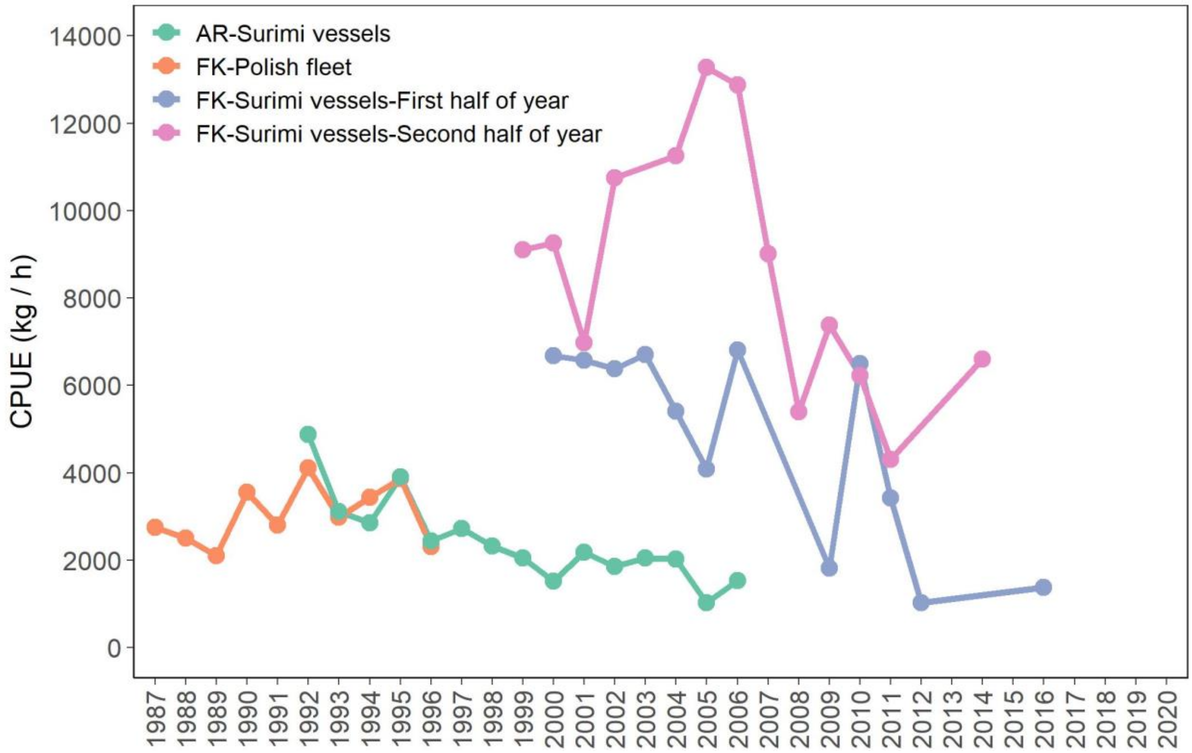

Fig. 6. Annual CPUE of southern blue whiting in Falkland Islands (FK) waters, calculated from the Polish fleet and surimi vessels (S–licence) during the first and second halves of the year, and annual CPUE of southern blue whiting in Argentine (AR) waters, calculated from surimi vessels.

The pooled length-age relationship of females and males (n = 10,325) gave: L_∞ = 59.09 cm, k = 0.1962, and t_0 = -1.5244 years (Fig. 7).

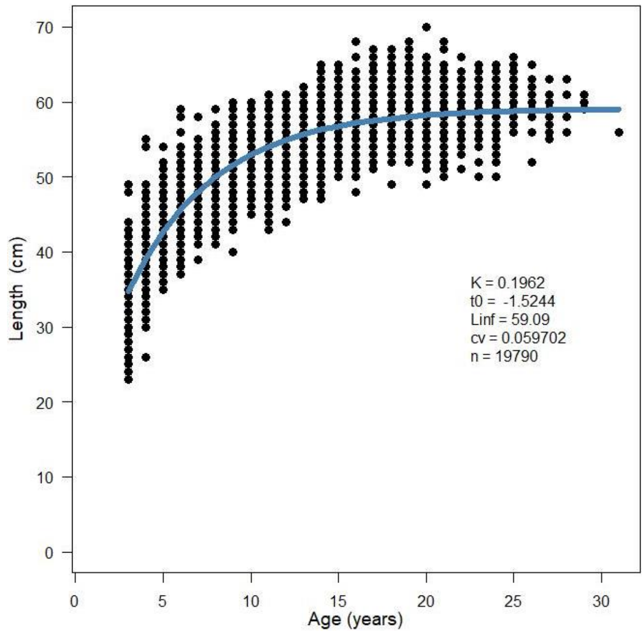

Fig. 7. von Bertalanffy age-length relationship of southern blue whiting from the Falkland Islands, females and males pooled. Note that ages 0, 1 and 2 are omitted.

Based on these age-length parameter values, and the FIFD age maximum of 28 years for southern blue whiting, the different natural mortality rates (M) examined were:

$$M = \frac{4.3}{t_{max}} = \frac{4.3}{28} = 0.1536$$ (Then et al. 2015)

$$M = 4.899 \times t_{max}^{-0.916} = 4.899 \times 28^{-0.916} = 0.2315$$ (Then et al. 2015)

$$M = 4.118 \times k^{0.73} \times L_\infty^{-0.33} = 4.118 \times 0.1962^{0.73} \times 59.09^{-0.33} = 0.3264$$ (Then et al. 2015)

$$M = 1.82 \times k = 1.82 \times 0.1962 = 0.3571$$ (Charnov et al. 2013)

where t_{max} = maximum age, L_∞ = asymptotic length, and k = rate by which L_∞ is approached. By comparison, southern blue whiting natural mortalities estimated in Chile were M = 0.32 for females and M = 0.34 for males (Aguayo et al. 2010), and M = 0.18 (Contreras et al. 2013). Natural mortality was estimated at M = 0.15 in Argentina (Giussi et al. 2007). Natural mortality of the disjunct sister population *Micromesistius australis pallidus* has been reported as M = 0.21 (Government of New Zealand on-line[d]).

[d] https://fs.fish.govt.nz/Doc/24379/86_SBW_2017.pdf.ashx

3.4.2. Estimation

Of the four natural mortality rates examined, only M = 0.15 showed stable convergence of the MCMC, with maximum posterior density estimates of B_0 and MSY bracketed within their 95% confidence intervals (Table VI; Appendix VIII). Moreover, with increasing M values, most parameter outputs increased monotonically but did not reach an asymptote. The CASAL model using M = 0.15 was therefore selected; all following estimates refer to the M = 0.15 model. B_{2020} was estimated at 617,757 t (512,482 – 875,453 t; 95% CI), which is approximately 61% of B_{1987} estimated at 1,008,210 t (936,418 – 1,217,471 t; 95% CI), whereas SSB_{2020} estimated at 555,913 t (446,573 – 794,118 t; 95% CI) was approximately 64% of SSB_{1987} estimated at 869,167 t (808,327 – 1,057,372 t; 95% CI); annual biomass estimates can be consulted in Appendix IX. MSY for the Southwest Atlantic, including Falkland Islands and Argentina, was estimated at 42,513 t (39,517 – 51,807 t; 95% CI) (Table VI; Appendix X). Taking the CASAL calculation of MSY as proxy for TAC in the Southwest Atlantic, alternatives of the Falkland Islands partition ranged from 1,985.36 t to 21,256.50 t (Table VII).

Estimated biomass increased from 1987 to 1991, followed by a decrease to reach the lowest biomass in 2010 (446,038 t; 317,658 – 665,271 t 95% CI). Estimated biomass then increased again from 2011 to 2020, the year when 617,757 t (512,482 – 875,453 t; 95% CI) were calculated (Fig. 8). The modest CASAL model increase from 2017 to 2020 (Appendix IX) is consistent with the increase in July survey biomass estimates between 2017 (estimated 1,610 t) and 2020 (9,490 t) (Table VIII). The proportionally much higher difference in the July survey biomass estimates was statistically significant, as 28,931 out of 30,000 paired re-samples had higher values in July 2020 than in July 2017 (96%), thus $p < 0.05$. In July 2017, aggregations of southern blue whiting were detected to the northeast in the FICZ, whereas in July 2020 aggregations were found to the southwest (Appendix XI), suggesting that differences in biomass may be due to differences in distribution.

Table VI. CASAL parameter Maximum Posterior Density estimates for southern blue whiting, with 95% confidence intervals in parentheses from MCMC distributions. The selected CASAL outputs are in bold font.

	CASAL			
M	**0.15**	0.23	0.33	0.36
B_0	**864,227** **(803,316 – 1,053,156)**	1,498,700 (1,223,208 – 1,497,460)	3,498,410 (2,823,396 – 3,495,021)	3,500,000 (3,486,760 – 3,499,210)
SSB_{1987}	**869,167** **(808,327 – 1,057,372)**	1,521,070 (1,244,816 – 1,522,270)	3,618,580 (2,926,118 – 3,627,980)	3,650,060 (3,583,330 – 3,722,184)
SSB_{2020}	**555,913** **(446,573 – 794,118)**	1,397,440 (978,965 – 1,669,463)	3,910,320 (2,788,218 – 5,073,110)	3,877,690 (2,908,704 – 5,271,822)
SSB_{2020}/SSB_{1987}	**0.6432** **(0.5427 – 0.7812)**	0.9324 (0.7140 – 1.1499)	1.1177 (0.8661 – 1.5011)	1.1079 (0.8331 – 1.5074)
B_{1987}	**1,008,210** **(936,418 – 1,217,471)**	1,978,030 (1,630,523 – 2,039,084)	5,664,890 (4,577,912 – 5,985,077)	6,098,650 (5,542,368 – 6,847,467)
B_{2020}	**617,757** **(512,482 – 875,453)**	1,655,560 (1,209,872 – 1,932,346)	5,138,250 (3,868,319 – 6,937,273)	5,286,070 (4,062,956 – 7,188,604)
B_{2020}/B_{1987}	**0.6127** **(0.5473 – 0.7191)**	0.8370 (0.7420 – 0.9477)	0.9070 (0.8450 – 1.1591)	0.8668 (0.7331 – 1.0498)
MSY	**42,513** **(39,517 – 51,807)**	111,823 (91,268 – 111,731)	357,513 (288,531 – 357,167)	361,837 (360,468 – 361,755)

Table VII. Total Allowable Catch (TAC) alternatives for southern blue whiting in Falkland Islands waters calculated from CASAL outputs.

Criteria	Threshold	TAC (t)
1) Relative average contribution		
10-year (19.28%)	42,513 x 0.1928	8,196.51
5-year (10.99%)	42,513 x 0.1099	4,672.18
3-year (4.67%)	42,513 x 0.0467	1,985.36
2) Equal share		
50%	42,513 x 0.5	21,256.50

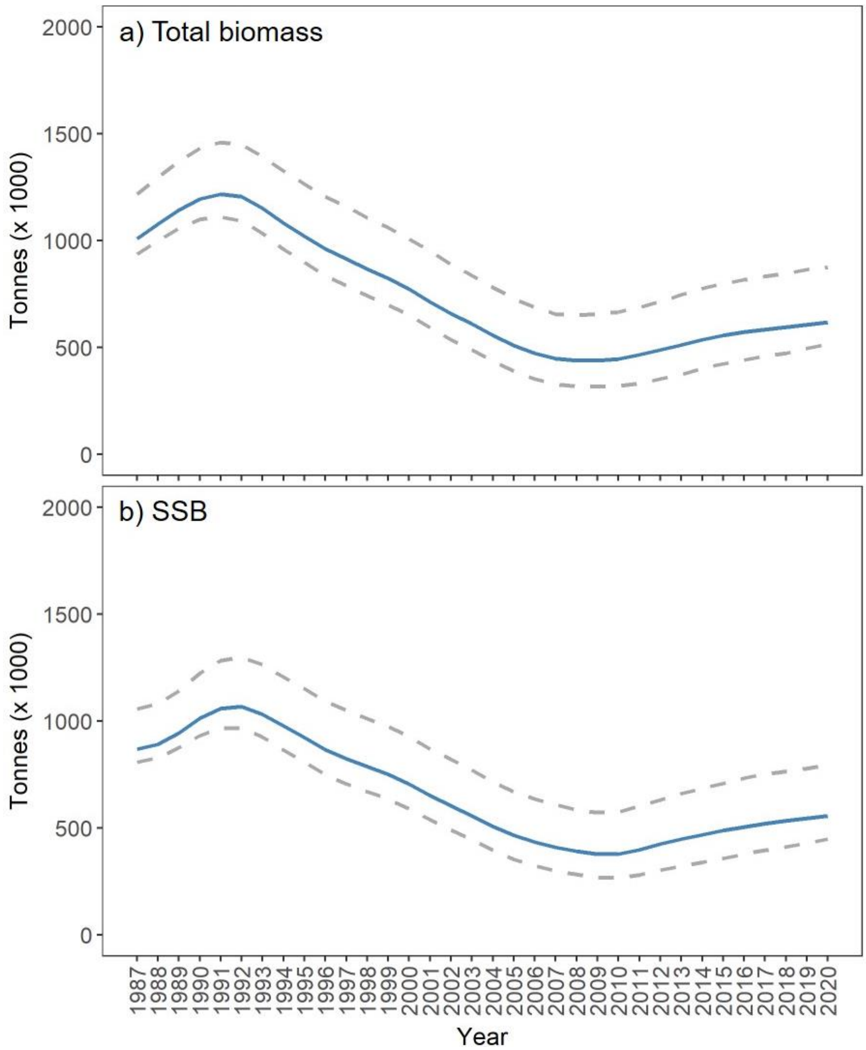

Fig. 8. Maximum Posterior Density estimates by the CASAL calculation of a) total biomass and b) spawning stock biomass (SSB) for southern blue whiting. 95% confidence intervals from MCMC posterior distributions are indicated by dashed lines. M = 0.15

Table VIII. Winter (July) surveys catch and effort, and biomass estimates (mean ± 95% confidence intervals) of southern blue whiting in Falkland Islands waters.

Year	Survey	Trawls (n)	Swept area (km^2)	Effort (h)	Catch (kg)	CPUE (kg/h)	Biomass (t)
2017	Groundfish	74	15.40	74	126.00	1.70	1610.11
	D. gahi[a]	59	54.70	114	574.27	5.04	(314.51 – 3078.74)
	Total	133	70.10	188	700.27	3.72	
2020	Groundfish[b]	33	7.14	33	605.56	18.34	9490.07
	D. gahi	55	98.57	101	56.20	0.56	(509.68 – 14664.33)
	Total	88	105.71	134	661.76	4.93	

[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 blue whiting.
[b]Twelve additional trawls were conducted in high seas during the July 2020 survey; these trawls were not included in the analyses.

The median SSB/SSB_0 ratio increased from 1987 through 1992; declined from 1992 through 2009, and then increased again through 2020. The projection of SSB/SSB_0 into the future showed an increase from 2021 through 2050, with wide 95% CI (Fig. 9).

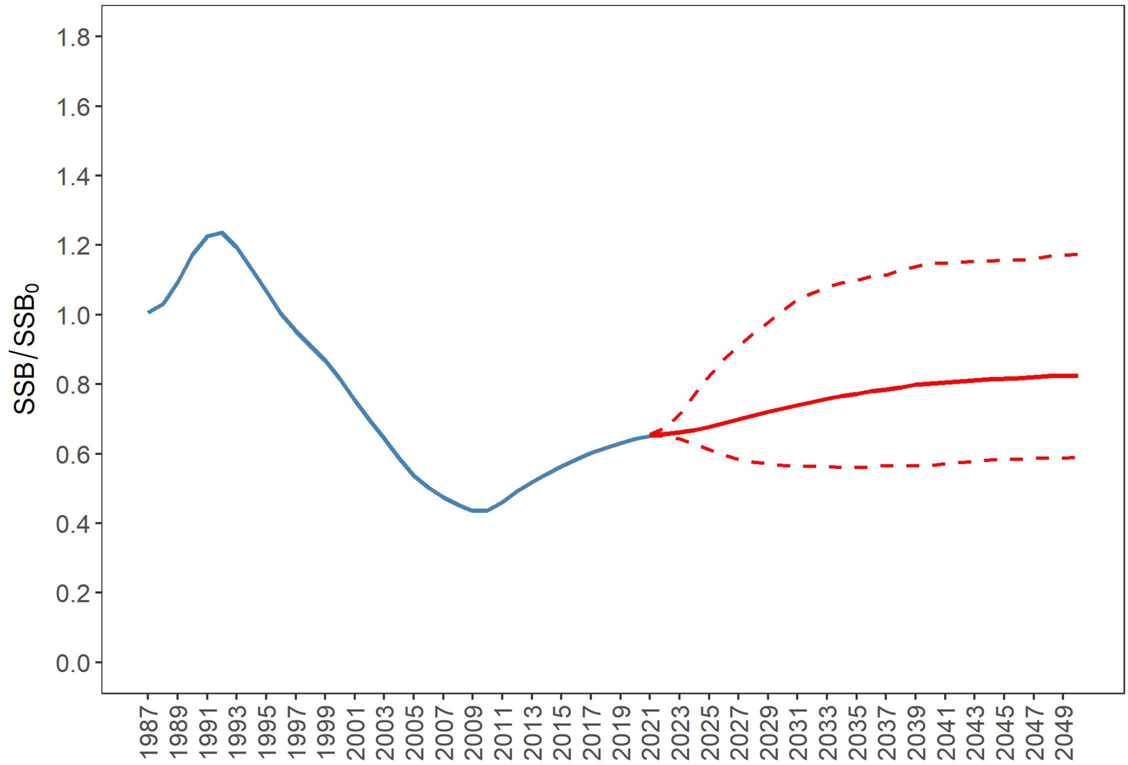

Fig. 9. SSB/SSB_0 trend from 1987 through 2020, and projected SSB/SSB_0 trend (red) into the future, with recruitment randomized on a lognormal distribution and constant annual catches assumed from 2021 – 2050. Solid line is the median and dashed lines are 95% confidence intervals.

4. Conclusions

Length-based indicators suggest that MSY and optimal yield were strong most years since 2002, with weak values from 2014 to 2018 and 2019 for females and males, respectively. This is probably because southern blue whiting has not been targeted over the last few years in Falkland Islands waters. For instance, surimi vessels used to target this stock sporadically since 1999. However, low catches and high operative costs prevented the surimi fleet from targeting southern blue whiting since 2017. Low catches have been due to the low abundance of this stock in the Southwest Atlantic for a number of years already. This is supported by relatively low biomass over the past 20 years compared with the high biomass in the early 1990s, based on CASAL calculations. The southern blue whiting stock shows signs of slow recovery with biomass increasing gradually from 2011 to 2020, and projections suggest further biomass increase through the year 2050. However, the projection had wide confidence intervals and should be taken with attention.

Conservation of mega-spawners was positive from 2002 to 2013 but was negative or of concern from 2014 to 2020. However, fewer large spawners were available, sampled and aged from 2014 to 2020, affecting the calculations of L_∞ and L_{Opt}, thus affecting the assessment for mega-spawners. Conservation of large individuals was positive from 2002 to 2020. Conservation of mega-spawners and large individuals may be in part due to a no-fishing area for the surimi fleet that was implemented 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 the positive trends in asymptotic lengths and the stable yearly length at 50% maturity for both females and males.

Length indicators for the conservation of immature individuals are more concerning because these were negative since 2010, and in particular for females that were more affected than males. It was found that 50% catch-at-age by surimi vessels was maximum 3.5–4.5 years in Falkland Islands waters, about the age at 50% maturity inferred from the length-age relationship. Therefore, by-catch avoidance and discard of small individuals that have not reached maturity should be of high importance in Falkland Islands fisheries given the trends detected.

The ICES category 5 Total Allowable Catch calculated for the Falkland Islands in 2022 (508 t) is 9× higher than the total commercial catch in Falkland Islands waters in 2020 (58 t), and Falkland Islands annual commercial catches have been decreasing for the last five years. The ICES category 5 TAC is nevertheless more conservative than even the lowest proportioned TAC options calculated from CASAL MSY estimates: 1,985.36 t. While the CASAL biomass trajectory for southern blue whiting was qualitatively similar to last year's trajectory calculated with a different method (Ramos et al. 2020), the absolute values of CASAL TAC estimates from MSY should be taken with care for several reasons: The total TAC (MSY = 42,513 t) was nearly twice as high as the TAC set in Argentina for 2021 (23,000 t; Government of Argentina on-line[e]), whereby Argentina takes the much greater proportion of southern blue whiting catch (and presumably does not recognize the Falkland Islands as a legitimate concurrent TAC holder). The abundance indices used in the CASAL model were no more recent than 15 years ago in the case of Argentine fisheries, and only sparsely used since then in the case of Falkland Islands fisheries (Falkland Islands Government 2021). Finally, MSY assumes a stock under equilibrium conditions (Jacobson et al. 2002; Bousquet et al. 2008), which the transition from a blue whiting dominated fishery to a rock cod dominated fishery to a hake dominated fishery (Winter & Ramos 2021) does not readily confirm. Given these caveats and 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 selected over CASAL TAC, and set at 508 t for 2022.

The multiple analyses used in this study suggest that the southern blue whiting stock is recovering slowly but still is in poor condition. Hence, conservation measures must be implemented, in particular for the conservation of immature individuals, by monitoring closely the by-catch and reporting of small and immature individuals.

[e] https://argentinambiental.com/legislacion/nacional/resolucion-14-20-captura-maxima-permisible-para-el-ano-2021/

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Appendix

Appendix I. Annual commercial catches (t) of southern blue whiting reported in Falkland Islands (excluding E–licence; Falkland Islands Government on-line[f]; Falkland Islands Government 2021), Argentina (Government of Argentina on-line[g]; Sánchez et al. 2012; Navarro et al. 2014, 2019) and Chile (Government of Chile on-line[h]; 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

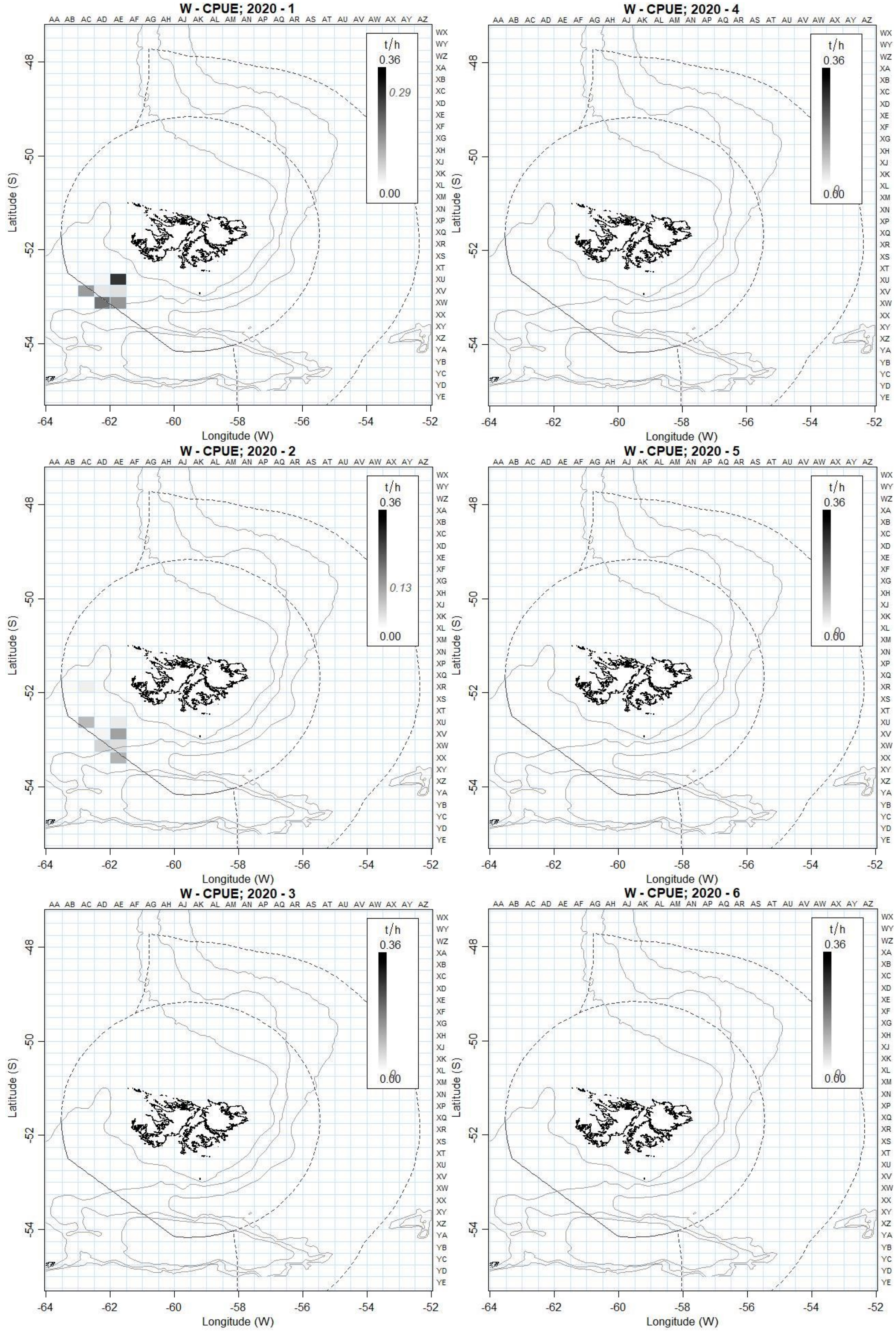
[f] http://www.fig.gov.fk/fisheries/publications/fishery-statistics
[g] https://www.agroindustria.gob.ar/sitio/areas/pesca_maritima/desembarques/
[h] http://www.sernapesca.cl/informes/estadisticas

Appendix II. Identifying finfish-licenced observer samples.

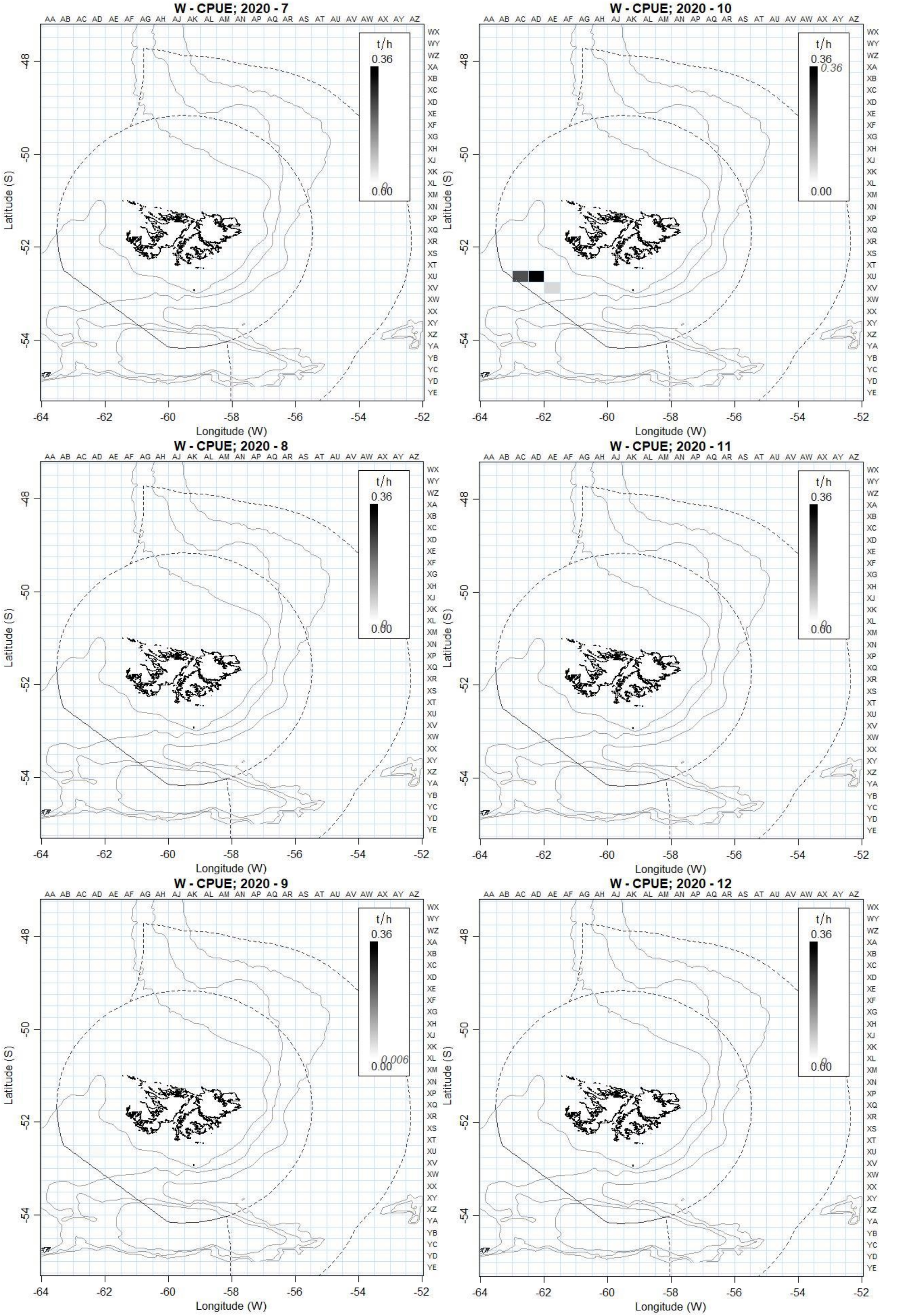
The FIFD observer database identifies samples by vessel, date, activity (fishing gear type), and observer station, but does not directly link to the licence that the vessel was operating under. If required, the licence must be cross-referenced from the catch report. In most cases, a catch report is recorded the same day by the same vessel, and the corresponding licence can be applied to the samples directly. In some cases however, a catch report is not recorded the same day and instead the nearest catch report by the same vessel either up to 3 days later or 1 day earlier is applied (which still does not result in all samples getting matched). The rationale being that a vessel will file its catch report when it has finished processing the trawl, which may be several days if it is a big haul or the factory is backed up; alternatively the observer might only sample a trawl the day after it was hauled.

Among positive licence matches, finfish trawl samples are those with activity codes B (bottom trawl), P (pelagic trawl) or S (semi-pelagic trawl), and licence codes A/Y (unrestricted finfish), G (*Illex* + restricted finfish), W/Z (restricted finfish), and S (surimi). Licence code E (experimental) may be any gear or catch target, and can therefore only be matched as finfish by checking against a survey report for that date range or, more expediently, evaluating the species composition that was caught. For this assessment, the criteria were used that a trawl E licence target was designated *Illex* if *Illex* comprised >50% of the catch within 1 day earlier and three days later, skate if skate comprised >50% of the catch within 1 day earlier and three days later, and calamari if calamari comprised >25% of the catch within 1 day earlier and three days later; otherwise finfish. The lower threshold for calamari reflected the outcome that calamari catch is often scarce in early days of pre-season surveys (e.g., Winter et al. 2019). As criteria of >50% *Illex* / skate vs. >25% calamari are non-exclusive, the additional rule was set that a catch composition was designated to that target which exceeded its threshold by the highest proportion. Finfish-designated E licence samples were then added to the commercial licence finfish samples.

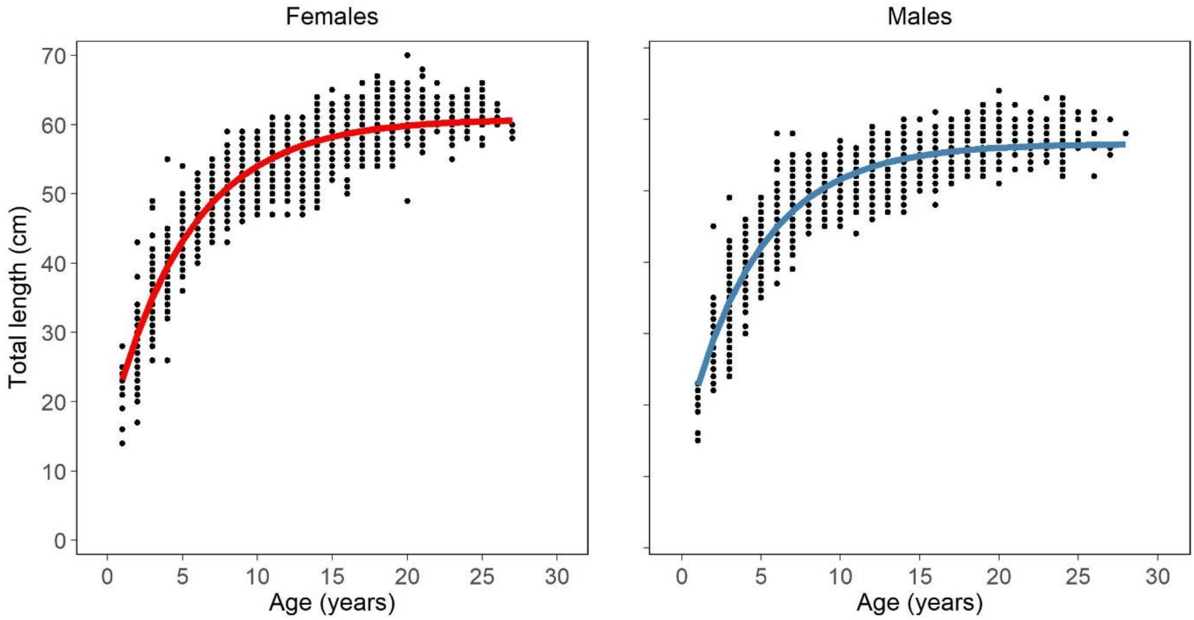
Appendix III. Monthly CPUE of southern blue whiting in Falkland Islands waters during 2020, estimated from W–licensed vessels.



Appendix III. *continued…*



Appendix IV. von Bertalanffy age-length relationship of female and male southern blue whiting from the Falkland Islands.

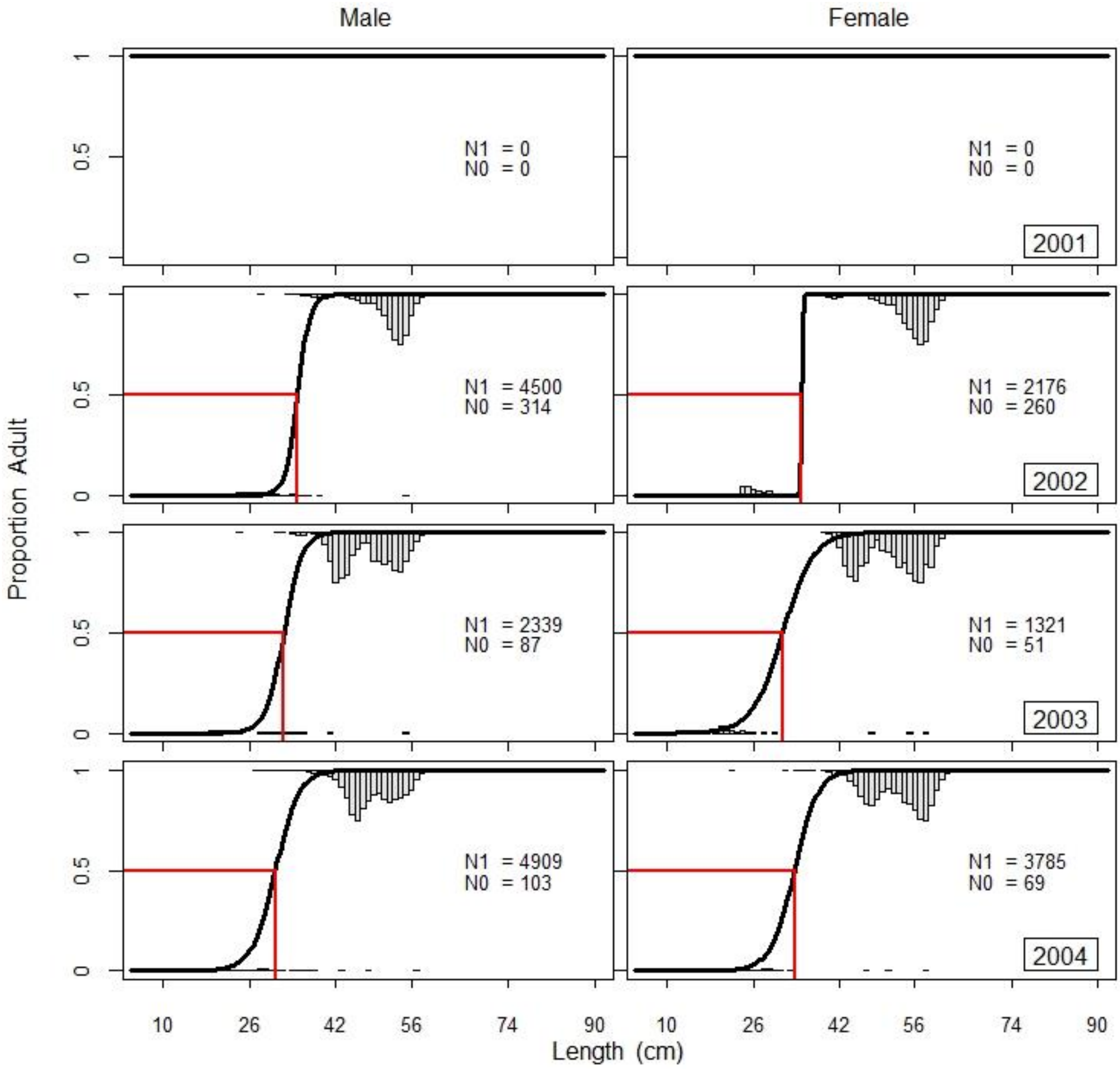


Appendix V. Southern blue whiting von Bertalanffy length-at-age parameters for curvature (k), age of fish at length zero (t_0), and asymptotic length (L_∞), by year and sex, with 95% confidence intervals.

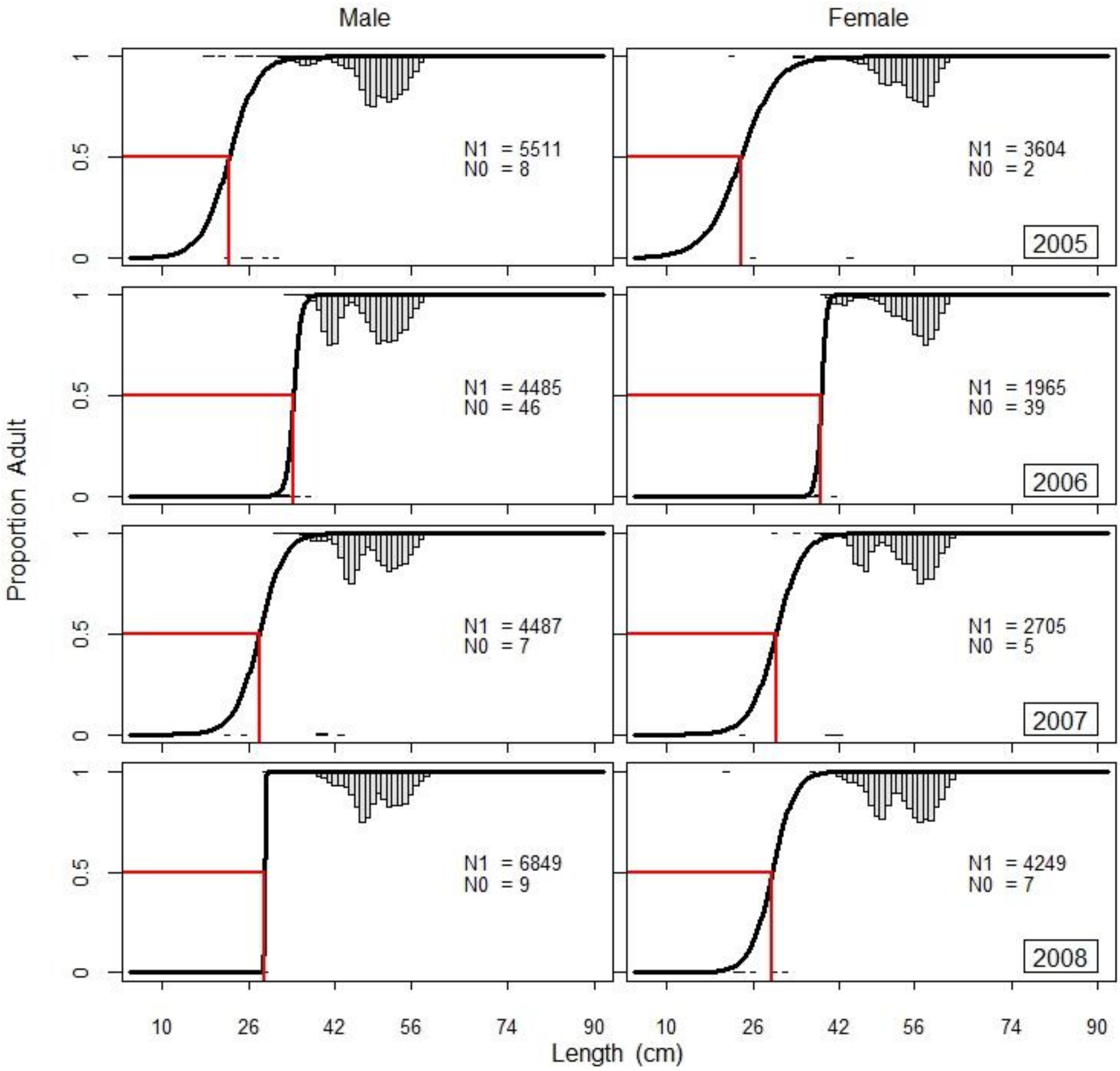
Sex	Year	N	k		t_0 (years)		L_∞ (cm)	
	1988	582	0.23	(0.21 - 0.24)	-1.16	(-1.47 - -0.91)	59.72	(58.9 - 60.7)
	1989	174	0.26	(0.22 - 0.29)	-0.68	(-1.07 - -0.33)	57.07	(55.5 - 58.6)
	1990	548	0.30	(0.29 - 0.31)	-0.09	(-0.14 - -0.04)	57.66	(57.0 - 58.3)
	1991	328	0.26	(0.24 - 0.28)	-0.74	(-1.00 - -0.51)	56.18	(55.2 - 57.2)
	1992	602	0.19	(0.18 - 0.20)	-1.73	(-1.96 - -1.53)	60.03	(59.2 – 61.0)
	1993	426	0.17	(0.16 - 0.18)	-1.59	(-1.78 - -1.41)	62.55	(61.9 - 63.3)
	1994	564	0.17	(0.15 - 0.18)	-2.07	(-2.52 - -1.65)	61.26	(60.1 - 62.5)
	1995	596	0.21	(0.19 - 0.22)	-1.30	(-1.60 - -1.04)	58.69	(57.9 - 59.6)
	1996	228	0.22	(0.20 - 0.23)	-1.09	(-1.45 - -0.78)	56.87	(56.1 - 57.8)
	1997	331	0.19	(0.17 - 0.22)	-1.72	(-2.25 - -1.25)	57.08	(55.9 - 58.5)
	1998	212	0.25	(0.21 - 0.30)	-1.00	(-1.69 - -0.43)	56.05	(54.9 - 57.4)
	1999	380	0.26	(0.24 - 0.29)	-0.57	(-0.91 - -0.26)	56.39	(55.8 - 57.1)
	2000	196	0.25	(0.22 - 0.28)	-0.93	(-1.51 - -0.44)	57.42	(56.7 - 58.2)
	2001	253	0.26	(0.24 - 0.29)	-0.50	(-0.92 - -0.14)	57.94	(57.4 - 58.6)
	2002	759	0.19	(0.18 - 0.21)	-1.85	(-2.16 - -1.58)	59.43	(58.7 - 60.2)
F	2003	319	0.22	(0.20 - 0.23)	-1.01	(-1.44 - -0.62)	60.67	(60.0 - 61.4)
	2004	411	0.21	(0.19 - 0.22)	-1.53	(-1.79 - -1.30)	60.47	(59.9 – 61.0)
	2005	183	0.30	(0.27 - 0.32)	0.09	(-0.28 - 0.39)	58.83	(58.3 - 59.4)
	2006	215	0.24	(0.22 - 0.25)	-0.80	(-1.03 - -0.59)	59.95	(59.3 - 60.6)
	2007	424	0.17	(0.16 - 0.19)	-2.21	(-2.64 - -1.81)	61.91	(61.2 - 62.7)
	2008	355	0.19	(0.18 - 0.21)	-1.59	(-1.98 - -1.24)	62.25	(61.6 – 63.0)
	2009	256	0.30	(0.28 - 0.32)	0.64	(0.50 - 0.76)	59.99	(59.5 - 60.5)
	2010	188	0.21	(0.19 - 0.23)	-1.33	(-1.83 - -0.89)	60.03	(59.1 – 61.0)
	2011	304	0.20	(0.19 - 0.22)	-1.50	(-1.77 - -1.25)	62.04	(61.4 - 62.7)
	2012	75	0.24	(0.21 - 0.28)	-0.71	(-1.28 - -0.23)	61.70	(60.6 - 62.8)
	2013	155	0.26	(0.24 - 0.27)	-0.29	(-0.47 - -0.12)	62.21	(61.5 - 62.9)
	2014	314	0.23	(0.22 - 0.25)	-0.52	(-0.64 - -0.40)	62.60	(61.8 - 63.4)
	2015	311	0.24	(0.23 - 0.26)	-0.30	(-0.45 - -0.17)	62.67	(61.6 - 63.7)
	2016	220	0.22	(0.20 - 0.24)	-0.92	(-1.22 - -0.64)	61.41	(60.3 - 62.6)
	2017	8	NA	(NA - NA)	NA	(NA - NA)	NA	(NA - NA)
	2018	0	NA	(NA - NA)	NA	(NA - NA)	NA	(NA - NA)
Sex	Year	N	k		t_0 (years)		L_∞ (cm)	
	1988	1086	0.32	(0.31 - 0.33)	-0.25	(-0.31 - -0.18)	54.26	(53.9 - 54.6)
	1989	169	0.23	(0.21 - 0.26)	-1.12	(-1.48 - -0.81)	55.79	(54.6 - 57.1)
	1990	780	0.32	(0.31 - 0.33)	0.05	(0.01 - 0.08)	54.41	(53.9 – 55.0)
	1991	319	0.24	(0.21 - 0.26)	-1.14	(-1.50 - -0.82)	55.05	(54.1 - 56.1)
	1992	614	0.22	(0.21 - 0.23)	-1.49	(-1.67 - -1.33)	55.46	(54.9 - 56.1)
	1993	409	0.19	(0.18 - 0.20)	-1.47	(-1.66 - -1.29)	57.44	(56.7 - 58.2)
	1994	472	0.16	(0.14 - 0.18)	-2.43	(-2.98 - -1.93)	59.39	(58.0 - 61.1)
	1995	626	0.26	(0.24 - 0.27)	-0.95	(-1.17 - -0.76)	53.74	(53.2 - 54.3)
	1996	207	0.24	(0.21 - 0.27)	-1.11	(-1.67 - -0.69)	53.38	(52.5 - 54.4)
	1997	266	0.24	(0.21 - 0.27)	-0.99	(-1.43 - -0.61)	53.67	(52.7 - 54.7)
	1998	238	0.22	(0.19 - 0.26)	-1.32	(-2.01 - -0.75)	54.41	(53.3 - 55.7)
	1999	367	0.27	(0.25 - 0.30)	-0.55	(-0.95 - -0.20)	53.36	(52.7 – 54.0)

M	2000	220	0.28	(0.24 - 0.32)	-0.88	(-1.55 - -0.32)	53.79	(53.0 - 54.7)
	2001	244	0.31	(0.28 - 0.34)	-0.25	(-0.60 - 0.04)	53.74	(53.2 - 54.4)
	2002	840	0.24	(0.23 - 0.25)	-1.19	(-1.42 - -0.98)	54.78	(54.3 - 55.3)
	2003	312	0.24	(0.22 - 0.27)	-0.77	(-1.14 - -0.44)	56.72	(56.1 - 57.4)
	2004	417	0.23	(0.21 - 0.25)	-1.24	(-1.51 - -0.98)	56.10	(55.4 - 56.7)
	2005	194	0.30	(0.27 - 0.33)	-0.47	(-0.78 - -0.19)	54.89	(54.3 - 55.5)
	2006	254	0.26	(0.24 - 0.29)	-0.83	(-1.10 - -0.60)	55.48	(54.6 - 56.4)
	2007	390	0.17	(0.16 - 0.19)	-3.01	(-3.55 - -2.51)	57.48	(56.7 - 58.2)
	2008	362	0.23	(0.22 - 0.25)	-1.23	(-1.49 - -0.99)	57.67	(57.1 - 58.3)
	2009	300	0.35	(0.31 - 0.39)	0.49	(0.25 - 0.71)	55.44	(54.6 - 56.3)
	2010	228	0.27	(0.25 - 0.30)	-0.75	(-1.14 - -0.39)	54.58	(53.8 - 55.4)
	2011	325	0.21	(0.20 - 0.22)	-1.55	(-1.81 - -1.32)	58.35	(57.8 - 58.9)
	2012	68	0.21	(0.18 - 0.24)	-1.03	(-1.74 - -0.46)	59.49	(58.2 - 60.8)
	2013	148	0.23	(0.21 - 0.25)	-0.58	(-0.83 - -0.36)	59.12	(58.1 - 60.2)
	2014	378	0.25	(0.24 - 0.26)	-0.54	(-0.65 - -0.44)	58.20	(57.5 - 58.9)
	2015	425	0.25	(0.23 - 0.26)	-0.35	(-0.46 - -0.25)	58.13	(57.3 – 59.0)
	2016	233	0.22	(0.20 - 0.24)	-1.09	(-1.42 - -0.79)	58.04	(57.0 - 59.1)
	2017	9	0.17	(0.03 - 0.51)	-1.90	(-7.41 - 1.38)	64.68	(53.1 - 141.6)
	2018	136	0.24	(0.21 - 0.28)	0.04	(-0.39 - 0.41)	58.30	(57.1 - 59.6)

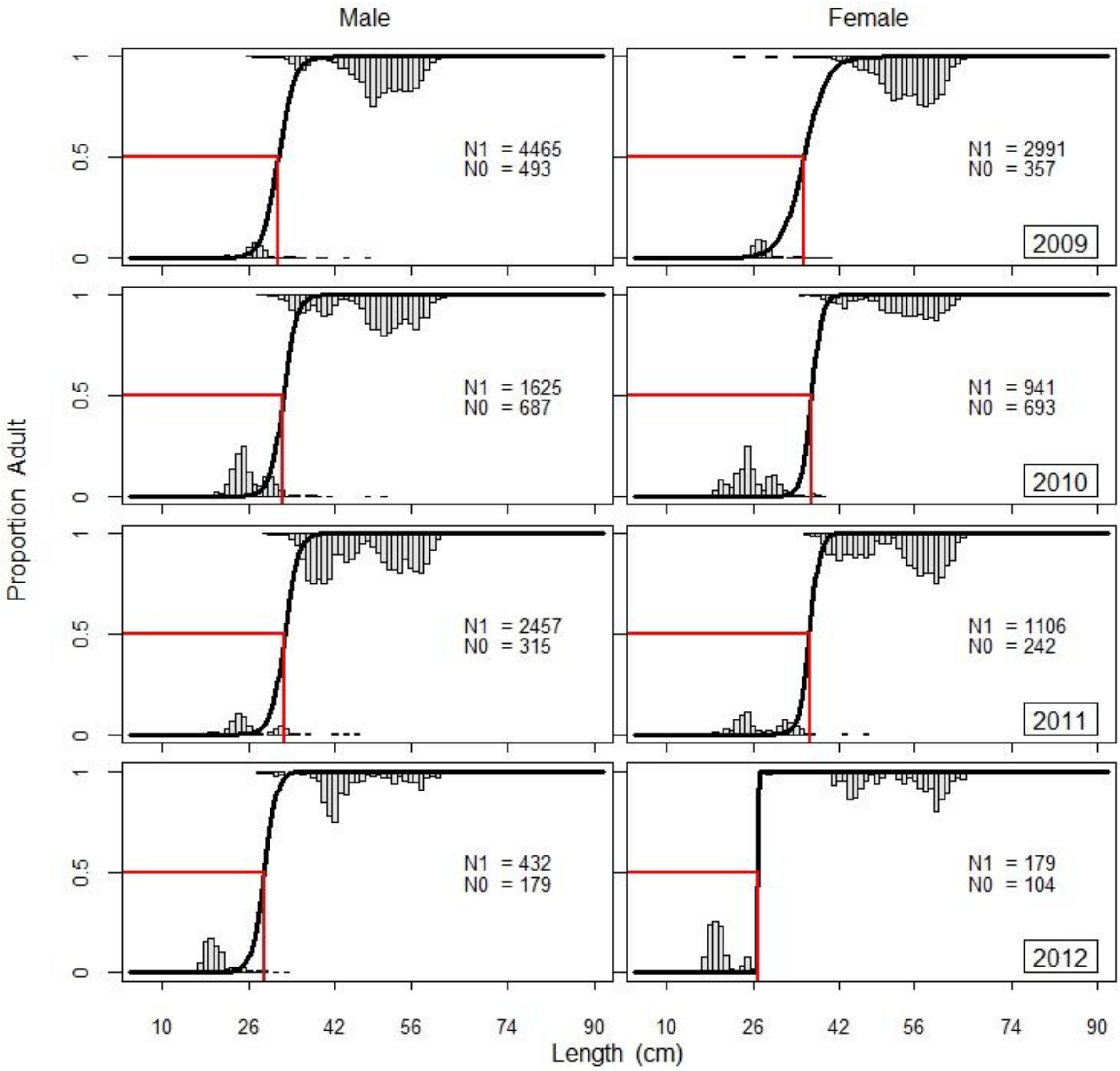
Appendix VI. Binomial logistic regressions of juvenile (0) or adult (1) maturity vs. length for southern blue whiting. Grey bars: distributions scaled to sample numbers. Red lines: Length intercept of 50% adulthood, corresponding to Fig. 4.



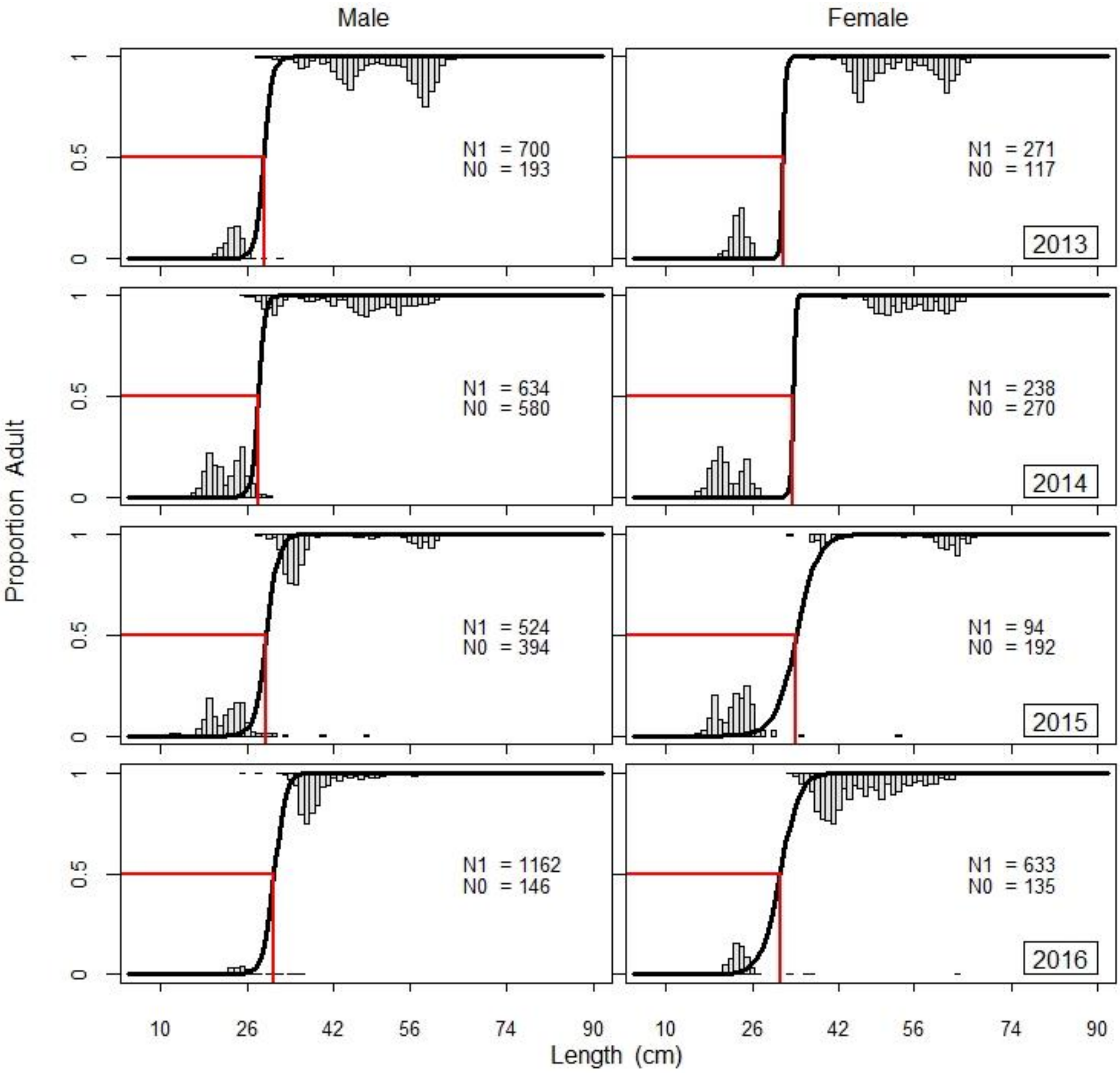
Appendix VI. *continued…*



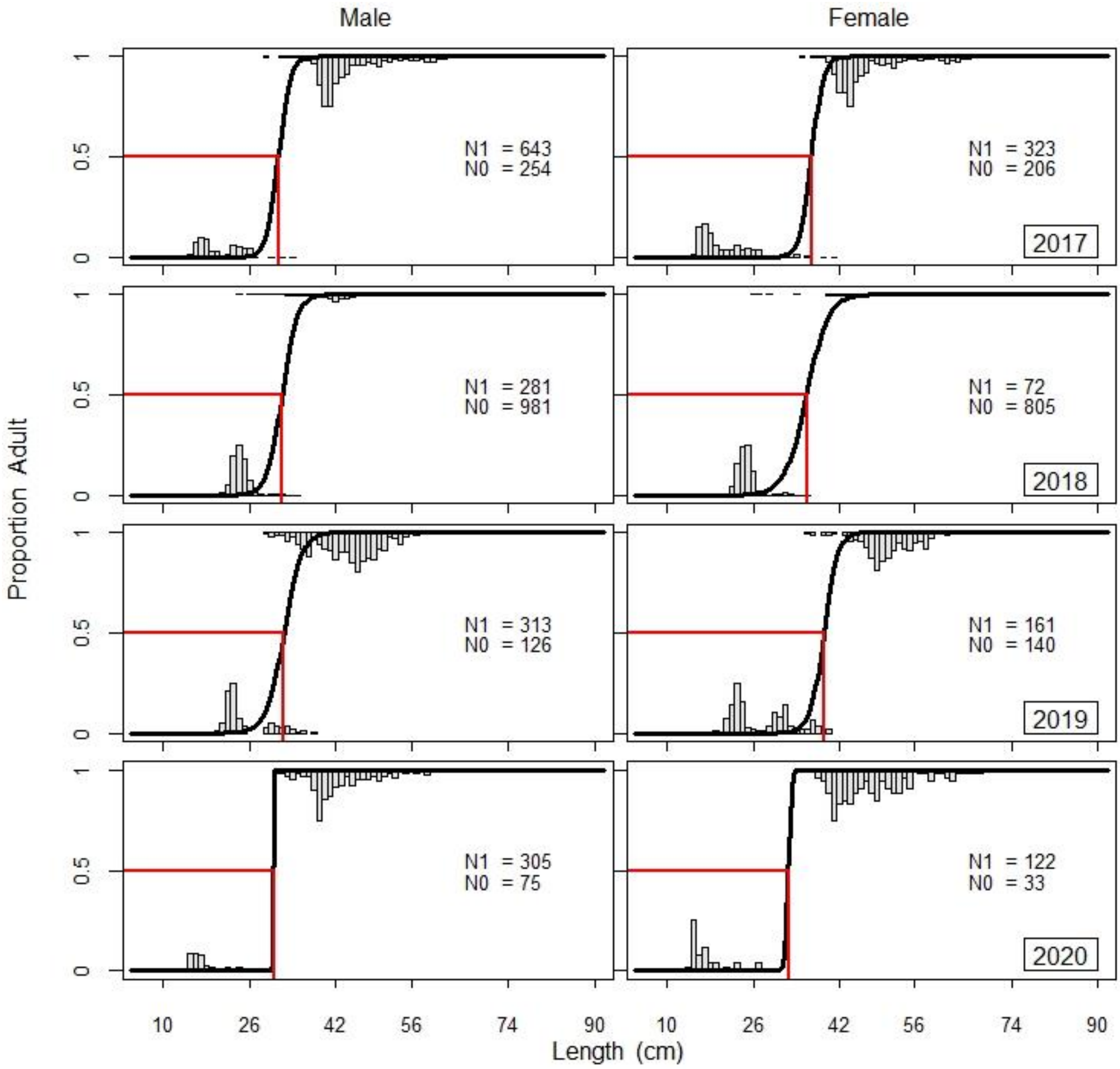
Appendix VI. *continued…*



Appendix VI. *continued…*



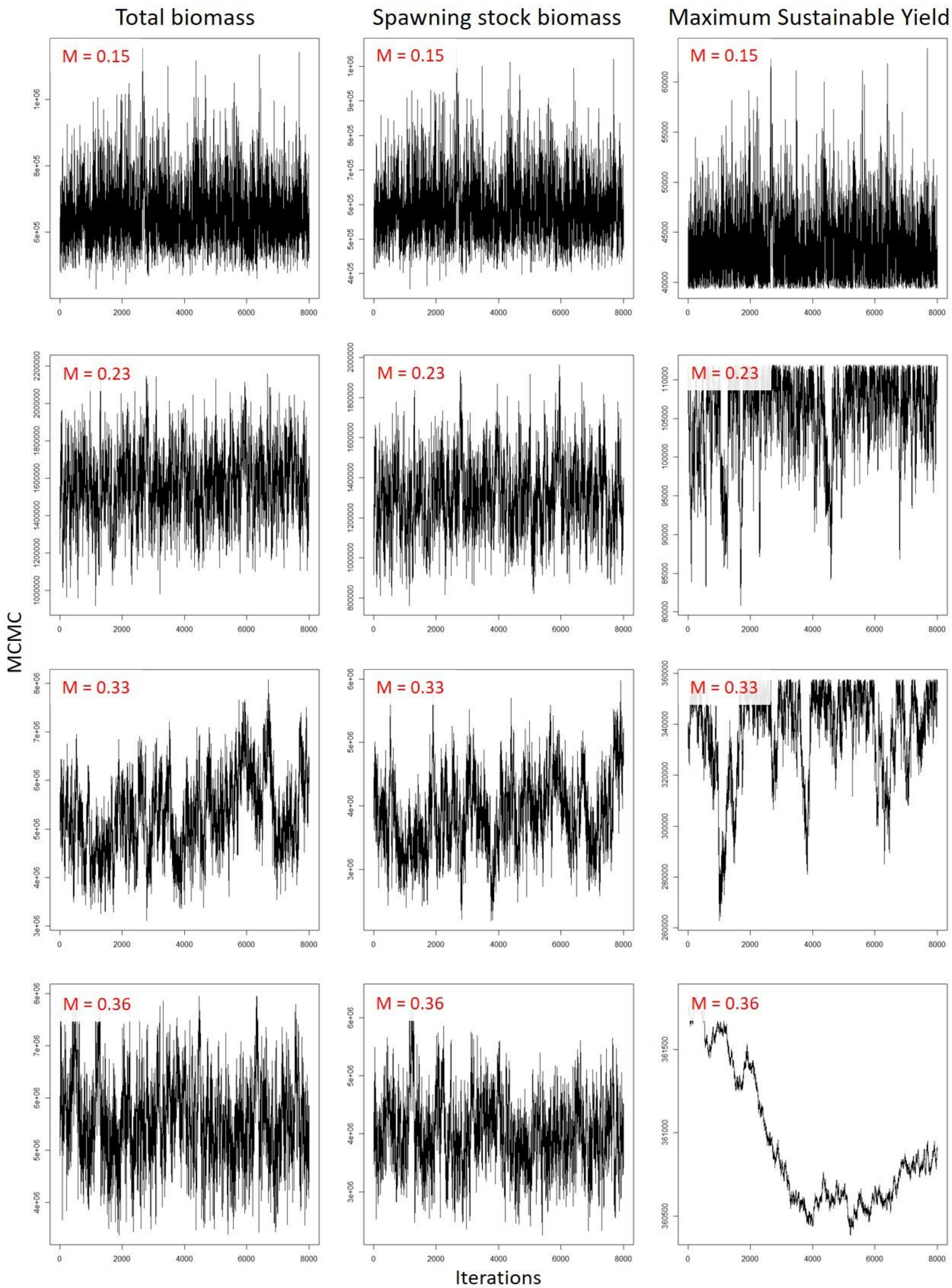
Appendix VI. *continued…*



Appendix VII. Number of southern blue whiting individuals sampled for length frequency distributions.

Year	Females (n)	Males (n)
2002	4,784	4,755
2003	1,939	2,304
2004	2,291	3,268
2005	3,995	4,039
2006	2,043	2,507
2007	1,225	1,377
2008	915	1,074
2009	3,137	4,677
2010	1,109	1,204
2011	1,333	1,208
2012	299	457
2013	954	1,172
2014	1,121	1,466
2015	810	1,025
2016	1,471	2,060
2017	643	944
2018	1,350	1,854
2019	523	587
2020	214	423

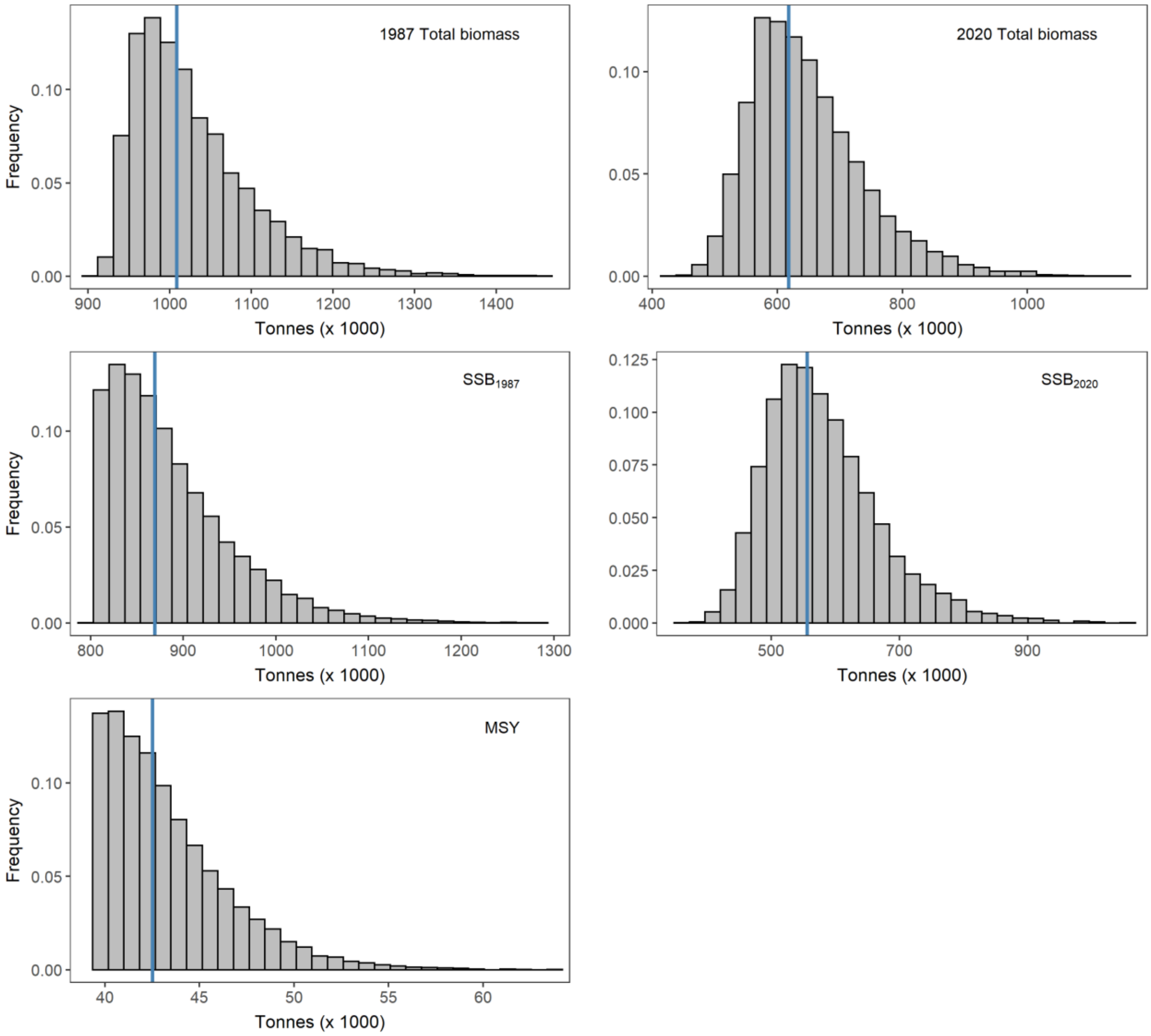
Appendix VIII. CASAL MCMC distributions of total biomass, spawning stock biomass, and maximum sustainable yield for the year 2020 using different natural mortality rates (M).



Appendix IX. CASAL total annual biomass and spawning stock biomass Maximum Posterior Density (MPD) estimates and 95% lower and upper confidence intervals (LCI and UCI, respectively) from MCMC posterior distributions for southern blue whiting. Estimates considering Falkland Islands and Argentina, with natural mortality (M) = 0.15

Year	Total biomass (MPD)	Total biomass (LCI)	Total biomass (UCI)	SSB (MPD)	SSB (LCI)	SSB (UCI)
1987	1,008,210	936,418	1,217,471	869,167	808,327	1,057,372
1988	1,076,390	998,809	1,295,353	890,335	828,823	1,081,643
1989	1,142,640	1,056,709	1,370,761	944,386	875,459	1,141,184
1990	1,195,050	1,099,155	1,433,629	1,012,940	932,102	1,224,165
1991	1,216,880	1,112,068	1,459,859	1,058,580	966,701	1,282,106
1992	1,205,830	1,092,719	1,450,916	1,068,090	967,447	1,298,915
1993	1,150,940	1,033,429	1,395,092	1,032,210	925,238	1,264,674
1994	1,081,450	959,797	1,325,374	976,877	863,921	1,206,278
1995	1,020,920	897,122	1,263,910	922,954	807,100	1,150,977
1996	962,655	837,451	1,207,266	866,262	749,073	1,092,244
1997	914,136	788,196	1,159,471	823,017	705,957	1,049,784
1998	865,753	740,824	1,106,922	786,569	668,459	1,012,311
1999	822,257	699,316	1,061,251	750,943	634,455	975,580
2000	772,847	650,632	1,009,846	705,308	590,506	927,162
2001	713,113	591,970	949,600	651,512	539,118	869,472
2002	657,125	535,796	889,865	603,286	491,539	821,039
2003	609,437	488,273	837,164	557,217	446,187	770,973
2004	556,592	435,580	779,508	506,943	395,935	715,603
2005	509,066	388,155	727,346	464,501	353,393	668,326
2006	472,104	351,960	686,506	434,405	322,745	635,134
2007	446,353	327,627	656,266	409,888	298,807	607,675
2008	438,473	317,394	652,240	391,524	281,560	584,622
2009	439,193	315,633	656,623	377,343	267,348	571,295
2010	446,038	317,658	665,271	378,109	266,172	574,035
2011	464,850	332,421	686,990	398,595	280,950	600,842
2012	487,856	351,254	713,968	425,243	302,152	631,409
2013	511,800	373,486	746,184	448,182	319,548	660,418
2014	536,559	401,070	776,487	468,668	337,585	685,703
2015	555,964	422,205	798,092	487,074	357,817	708,423
2016	571,588	440,659	815,650	505,005	377,592	731,948
2017	583,873	458,515	832,030	520,304	395,001	749,806
2018	594,355	473,169	846,200	532,379	410,649	763,733
2019	606,318	493,923	863,595	544,629	427,913	778,366
2020	617,757	512,482	875,453	555,913	446,573	794,118

Appendix X. MCMC posterior distributions of CASAL model estimates of total biomass and spawning stock biomass (SSB) in the first (1987) and last (2020) years in the time series, and MSY for southern blue whiting. Maximum Posterior Density estimates are indicated by the blue line. Estimates considering Falkland Islands and Argentina, with natural mortality (M) = 0.15



Appendix XI. Densities of southern blue whiting modelled by inverse distance weighting throughout the Falkland Islands fishing zone, in July 2017 and July 2020.