Stock Assessment of hoki (*Macruronus magellanicus*) in the Falkland Islands

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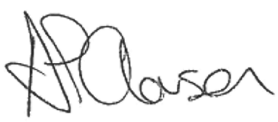

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Summary

Commercial catches of hoki *Macruronus magellanicus* in Falkland Islands licenced fisheries were 7,629 tonnes (t) in 2020, the eighth lowest catch since 1990. Nearly 97% of the commercial catches were by finfish licences (G–, and W–). Fishing effort decreased steeply since the early 2000's; as a result, commercial CPUE in 2020 was the second highest level (1,018 kg/h) since 1990. In contrast, CPUE from summer (February) surveys had its third lowest level (75 kg/h) in 2020 since 2010.

Following recommendations of the MacAlister Elliott & Partners external review, Total Allowable Catch (TAC) was calculated according to the ICES category 5 assessment framework: three-year catch average. The hoki TAC for 2022 is recommended at 6,478 t, which represents a decrease of 15% from the total commercial catch in 2020 (7,629 t).

Length-based indicators were scored on a traffic-light scale of green, yellow, red. Conservation of immature individuals and large individuals was of concern (yellow) or negative (red), and conservation of mega-spawners was negative since 2002. Optimal yield was of concern or negative, mainly for females. Maximum sustainable yield was negative for females, except from 2006 to 2015. Maximum sustainable yield fluctuated for males but was negative since 2017. Asymptotic lengths (L_∞) increased significantly over the past decade for males. However, lengths at 50% maturity decreased since 2011 for females and since 2002 for males. Individuals > 25 cm pre-anal length size classes and ≥ 4 years old were dominant early in the time series (i.e., 2002–2003, and 2006–2007). Individuals < 25 cm pre-anal length and < 4 years old were more common in the following years, with a peak of nearly 15 cm pre-anal length and 1-year old individuals observed in 2017. Recruitment to the fishery of 1– and 2–years old individuals was detected every 2 to 4 years.

Introduction

Hoki *Macruronus magellanicus* Lönnberg, 1907 (Merlucciidae) is a highly migratory pelagic-demersal fish that inhabits 30–500 m depth (Froese & Pauly 2021). This species occurs in temperate shelf and slope waters of the Southeast Pacific from 29°S (southern Chile) and of the Southwest Atlantic from 33°S to 57°S around Cape Horn, including Argentina and Falkland Islands (Wöhler & Giussi 2001; Schuchert et al. 2010; Froese & Pauly 2021). Hoki is one of the most abundant species on the Patagonian shelf; however, it is not highly abundant in Falkland Islands waters as the Falkland Island Conservation Zone is located at the edge of its distribution (Falkland Islands Government 2021). Hoki in the Southwest Atlantic and in the Southeast Pacific belong to the same population (McKeown et al. 2015), via migrations around Cape Horn and throughout the channels of Tierra del Fuego (Wöhler & Giussi 2001). In agreement with these findings, genetic studies found that individuals from the Argentine coast, and from near the west (52°S, 64°W) and southwest (54°18'S, 64°43'W) edge of the Falkland Island Conservation Zone belong to the same population (D'Amato & Carvalho 2005; D'Amato 2006). Therefore, hoki from the Falkland Islands, Argentina and Chile will be considered as a single stock for the purpose of this report.

The main spawning aggregations have been encountered in the vicinity of Guamin Island, Chile, between 43°S and 48°S (Payá et al. 2002). Smaller aggregations of spawning fish and juveniles have also been found in the Southwest Atlantic in the Gulf of San Matias and in the Gulf of San Jorge in Argentina (Wöhler & Giussi 2001), and on the shelf edge east of the Falkland Islands (Giussi 1996). Larvae are present on either side of the Magellanic Strait (53°S), near Cape Horn (55°S), and farther north in coastal areas of the Atlantic Ocean (Niklitschek et al. 2014). After winter spawning, part of the hoki population migrates in spring to feeding grounds in the slope areas of the Falkland Current Front (west of the Falkland Islands) (Brickle et al. 2009; Arkhipkin et al. 2012), and in summer it mainly occupies the warmer northern Falkland Islands' shelf (Brickle et al. 2009).

Methods

ICES advice rules

In 2020, hoki 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, 2018a), referencing applicable categories of data availability and quality. MEP (2020) recommended using a category 5 assessment framework for hoki. MEP (2020) also recommended exploring ancillary stock status information from ICES data limited methods such as length-based indicators. Therefore, a Length-Based Indicator method (LBI) (ICES 2015) was used to provide a suite of indicators based on combinations of catch-at-size distributions and life-history parameters.

Commercial fishery data

Commercial fishing around the Falkland Islands was not distinguished from other parts of the Southwest Atlantic prior to 1982 and catch data by species were recorded systematically from 1987 only (Falkland Islands Government 1989). Therefore, total hoki catch data were examined from 1987 to 2020 (Falkland Islands [http://www.fig.gov.fk/fisheries/publications/fishery-statistics; Falkland Islands Government 2021], Argentina [https://www.agroindustria.gob.ar/sitio/areas/pesca_maritima/desembarques/; Sánchez et al. 2012; Navarro et al. 2014, 2019], and Chile [http://www.sernapesca.cl/informes/estadisticas; SERNAPESCA 1990, 2000, 2011, 2021]). LOESS (span = 0.75, degree = 2) was implemented to examine the pattern of the association between Falkland Islands and Argentine, and between Falkland Islands and Chilean commercial annual catches of hoki from 1987 to 2020.

Commercial catches of hoki in Falkland Islands waters were examined by licence type for 2020. Exploratory analysis showed that finfish G– and W–licences contributed most hoki catch and catch-per-unit-effort (CPUE) across years. Therefore, spatial distribution of the 2020 monthly CPUE average was estimated from G– and W–licences, excluding the finfish A–licence. CPUE was also estimated per year and per month from G– and W–licences only.

Scientific surveys data

Biomass estimates and the spatial distribution of hoki were examined from austral summer scientific surveys (groundfish and *D. gahi* pre-season surveys) carried out in February 2010, 2011, and 2015 – 2021 in Falkland Islands waters (Ramos & Winter 2021). A trend of the biomass time series from 2010 to 2021 was calculated using LOESS (span = 0.75, degree

= 2). Biomass ratios between the most recent February surveys (2021) and the first February surveys (2010) were estimated as a proxy of the change in biomass over time. Significance of difference and 95% confidence intervals of the change in biomass were computed from the randomized re-samples of the survey biomass estimates (Ramos & Winter 2021). Biomass estimates, the spatial distribution of hoki, and biomass ratios were also examined (following Ramos & Winter 2021) 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).

ICES Category 5 Total Allowable Catch

The category 5 assessment framework is based on the average catches from the 3 previous years (MEP 2020). Therefore, Total Allowable Catch (TAC) for the year 2022 was estimated based on the in-zone average catch from 2018 to 2020, excluding experimental (E–licence) and out-of-zone catches (O–licence), whereby no hoki catches were reported out-of-zone during those years:

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

Where C = Catch (t).

Length analyses

Length Based Indicators

ICES (2015, 2018b) recommends the LBI method, which provides a suite of indicators based on combinations of catch-at-size distributions, life-history parameters such as L_∞ (Haddon 2001) and L50 (length at 50% maturity; Cope & Punt 2009). L_∞ and L50 parameters were assessed for females and males separately.

LBI method was applied to all years from which observer length measurements of hoki were available and reported as random samples (FIFD database codes R and S), i.e., years 2002 to 2020. Pre-anal lengths of up to one hundred individuals were measured to the lowest centimetre per trawl. 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 hoki.

The procedure for identifying finfish-licensed observer samples is described in Appendix I. 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} / $L_{Opt} \approx 1$).
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} / $L_{F=M} \geq 1$). $L_{F=M}$ 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 $(3 \cdot L_C + L_\infty)/4$.

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 1.0, 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 for MSY was scored the same as >1, except that empirical values ≥1 were automatically green.

Length-age relationship

L_∞ was calculated from the von Bertalanffy growth function, modelled to hoki length and age data from the FIFD database with nonlinear least-squares fitting using the R package ‘fishmethods’ (Nelson 2019). Hoki 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 the von Bertalanffy parameters were calculated by LOESS (span = 0.90, degree = 2, weighted by inverse variance), and the LOESS smooth fits applied to the LBI indicators to mitigate unevenness over the time series.

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 (Winter 2018). Hoki maturities were available from all years 2002 to 2020. 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. These LOESS smooth fits were also used for LBI parameterization per year.

Length frequencies

Length frequencies were examined yearly for females and males separate to describe patterns in length from 2002 to 2020. Lengths of individuals sampled randomly (FIFD database codes R and S) on finfish bottom trawl vessels, i.e., G–, and W– licences, were included in the analysis. Juveniles and unsexed individuals were excluded from the analysis.

Results

ICES advice rules

Commercial fishery data

Hoki catches in Falkland Islands waters have averaged 4,129 t per year since 1987, representing approximately 9% of the Falkland Islands, Argentine, and Chilean combined annual catch (Fig. 1; Appendix II).

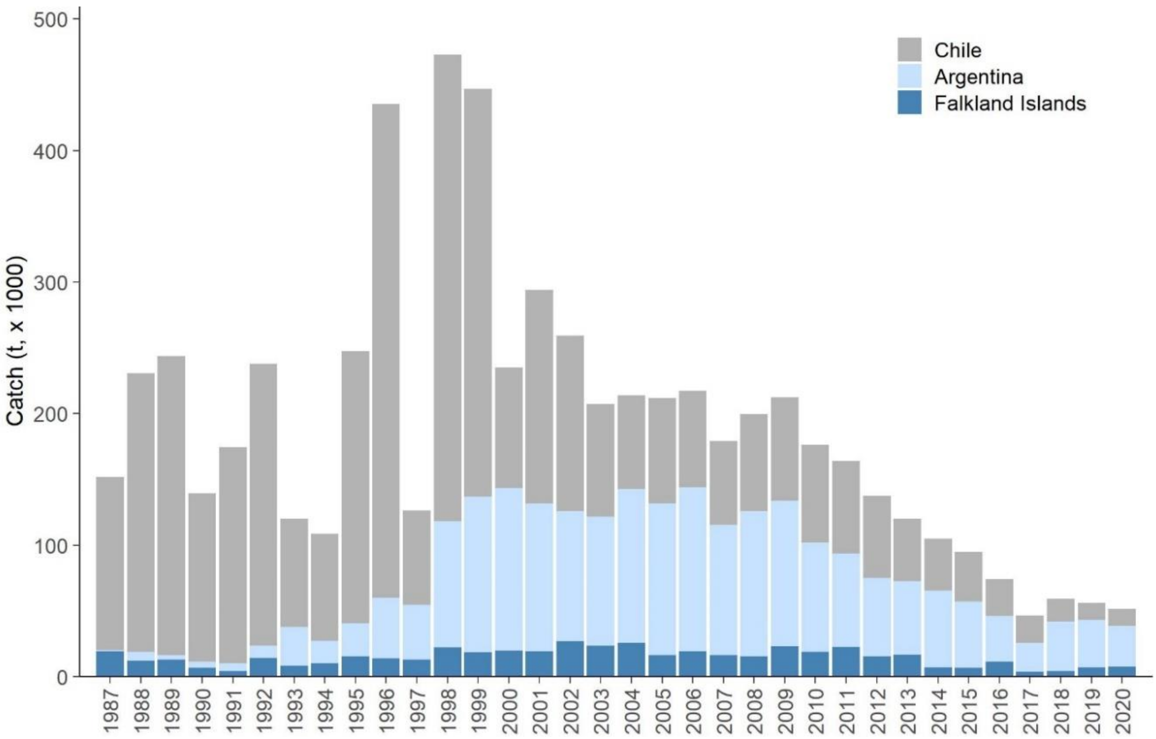

Fig. 1. Annual commercial catch of hoki in Falkland Islands, Argentine and Chilean waters. Falkland Islands commercial catch data exclude experimental (E–licence) and out-of-zone (O–licence) licences.

Falkland Islands and Argentine annual hoki catches were significantly positively associated when Argentine catches were approximately between 30,000 t and 95,000 t. Falkland Islands and Chilean annual hoki catches were significantly positively associated for Chilean catches up to approximately 100,000 t (Fig. 2).

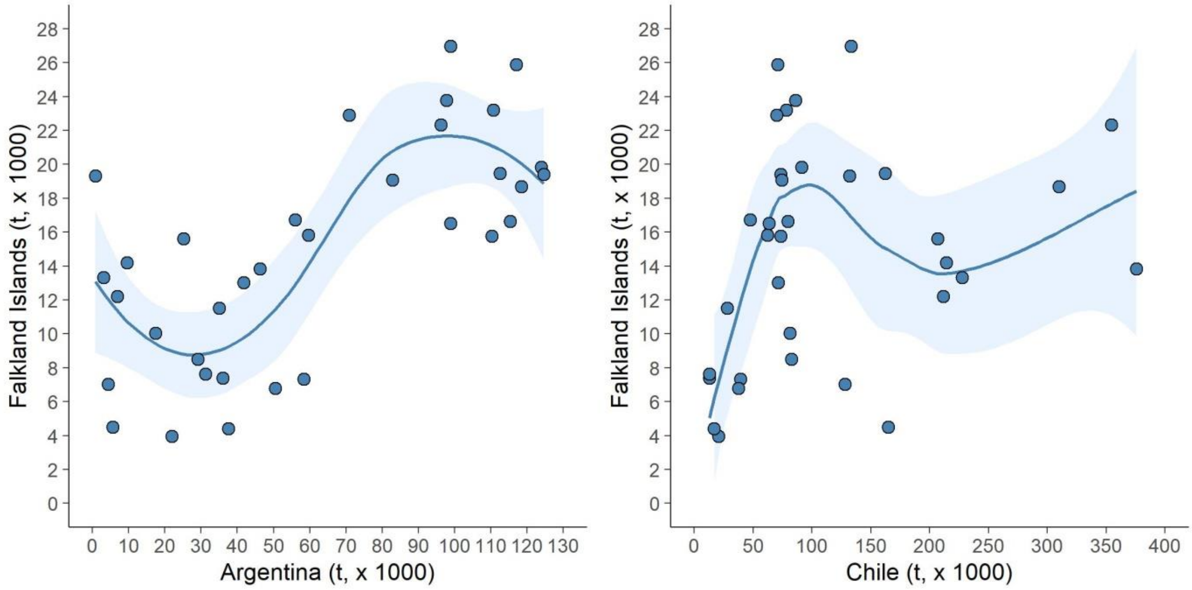

Fig. 2. Annual commercial catches of hoki, Falkland Islands vs. Argentina (left) and Falkland Islands vs. Chile (right), from 1987 to 2020. Blue lines: LOESS smooths ± 95% confidence intervals.

During 2020 a total of 7,643 t of hoki were reported caught in Falkland Islands waters, of which 7,629 t were reported under commercial licences, i.e., excluding the experimental E–licence. Two finfish licences alone (W– and G–licences) accounted for 97% of the total hoki catch (Table I).

Table I. Catches by licence of hoki in Falkland Islands waters during 2020.

Licence	Target species	Catch (t)	Catch (%)
W	Restricted finfish	5938.12	77.69
G	Restricted finfish and *Illex*	1445.98	18.92
A	Unrestricted finfish	128.38	1.68
C	Calamari 1st season	87.63	1.15
X	Calamari 2nd season	29.20	0.38
E	Experimental	13.84	0.18
B	*Illex* squid	0.15	0.00
F	Skates and rays	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		7,643.30	100.00

W– and G–licence CPUE had an increasing trend in the time series; the highest CPUE was recorded in 2019 (1,211 kg/h) and the second highest CPUE occurred in 2020 (1,018 kg/h) (Fig. 3).

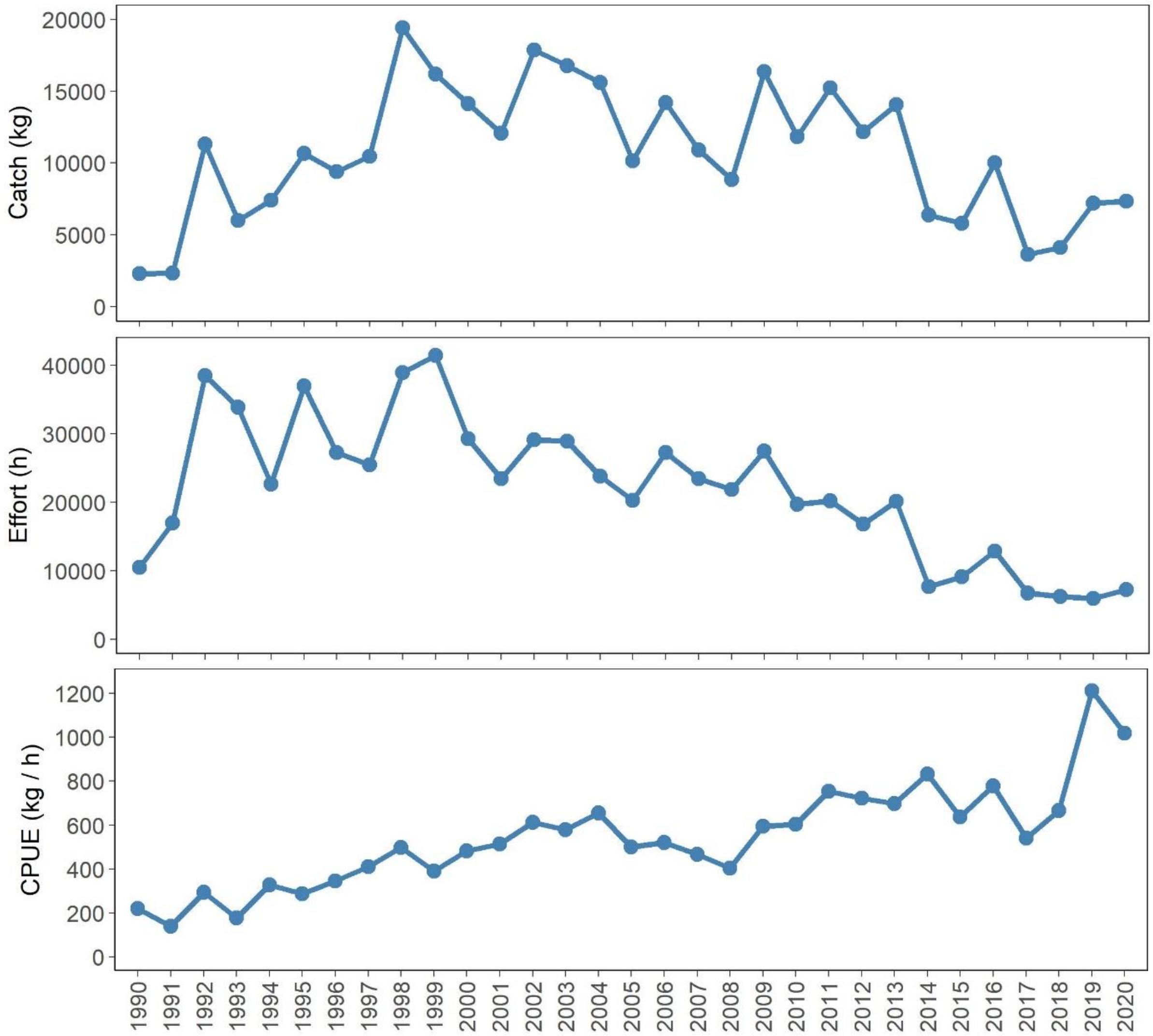

Fig. 3. Yearly catch, effort, and CPUE of hoki in Falkland Islands waters, calculated from G– and W–licensed vessels.

Average monthly CPUE since 1990 had a declining trend from January through December, with the highest values recorded in February (729 kg/h), March (737 kg/h), and April (684 kg/h). Secondary peaks were observed in June and in October; the peak in June at > 200 m depth represents the subadult slope foraging immigration and at < 200 m depth represents the adult shelf spawning emigration (Laptikhovsky 2007). In 2020, the highest CPUEs were recorded in January and February (1,798 kg/h and 1,427 kg/h, respectively). Secondary peaks were also evident in June (994 kg/h) and in October (1,008 kg/h) (Fig. 4;

Appendix III). Hoki were caught mainly to the west and southwest of West Falkland, between 51°S and 53°S, and between 61°W and 63.5°W mainly during the first half of 2020; minor catches were also reported to the north in the FICZ (Appendix IV).

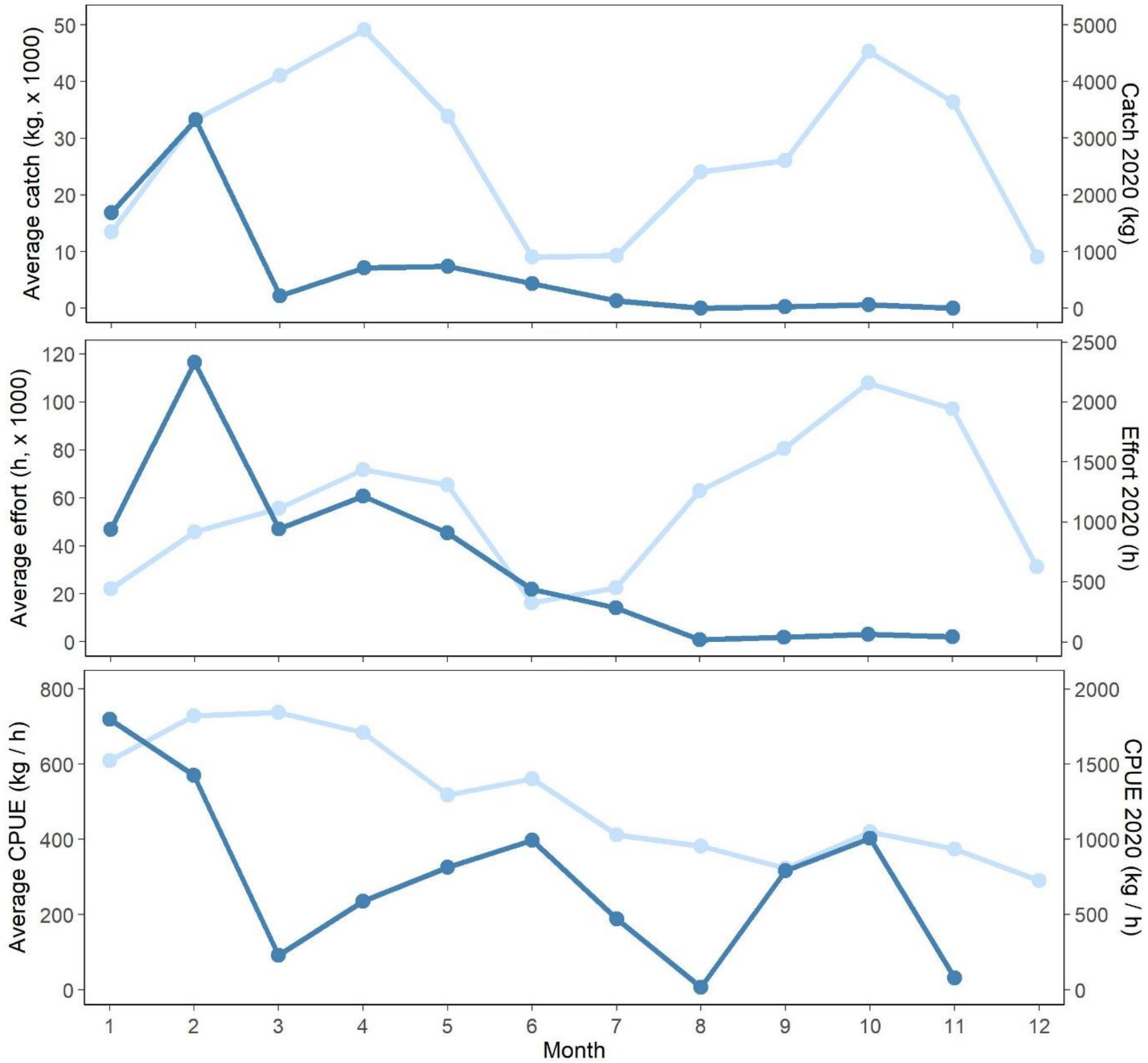

Fig. 4. Average monthly catch, effort, and CPUE of hoki in Falkland Islands waters for 2020 (dark blue line), and average since 1990 (light blue line), calculated from G– and W–licensed vessels.

Scientific surveys data

Summer surveys (February)

The biomass of hoki during the 2021 February surveys (312,118 t) was 1.1× the biomass of the 2010 February surveys (272,080 t; Table II; Fig. 5). However, only 14,376 out of 30,000 paired re-samples had higher biomass estimate values in February 2021 than in

February 2010 (47.9%), therefore not significant at $p > 0.05$. During the February surveys, hoki were dispersed through the FICZ in 2010, 2011, and 2015. From 2016, hoki were mainly aggregated to the southwest edge of the FICZ (Appendix V).

Table II. Summer (February) surveys catch and effort, and biomass estimates (mean ± 95% confidence intervals) of hoki in Falkland Islands waters.

Year	Survey	Trawls (n)	Swept area (km^2)	Effort (h)	Catch (kg)	CPUE (kg/h)	Biomass (t)
2010	Groundfish	87	17.04	87.52	49656.01	567.39	272080.22 (197644.96–472481.97)
	D. gahi	55	42.29	109.27	30124.00	275.69	
	Total	142	59.33	196.79	79780.01	405.42	
2011	Groundfish	88	17.21	88.00	28405.39	322.79	225981.56 (173396.03–287362.59)
	D. gahi	58	40.04	110.63	27594.30	249.42	
	Total	146	57.25	198.63	55999.69	281.92	
2015	Groundfish	89	16.72	90.17	9768.23	108.34	129562.42 (40753.69–175529.10)
	D. gahi	57	46.90	111.50	16596.00	148.84	
	Total	146	63.61	201.67	26364.23	130.73	
2016	Groundfish	90	17.64	91.42	21666.57	237.01	167312.12 (83510.52–231697.65)
	D. gahi	56	54.46	107.92	17248.42	159.83	
	Total	146	72.10	199.33	38914.99	195.23	
2017	Groundfish	90	18.52	92.00	3206.21	34.85	28863.12 (16842.07–39751.29)
	D. gahi	58	54.09	117.00	488.32	4.17	
	Total	148	72.62	209.00	3694.53	17.68	
2018	Groundfish[a]	97	20.47	96.42	29334.80	304.25	139665.90 (91380.06–203699.81)
	D. gahi	59	36.87	100.83	682.10	6.76	
	Total	156	57.35	197.25	30016.90	152.18	
2019	Groundfish	79	17.22	79.00	7315.40	92.60	41346.89 (6569.34–188598.04)
	D. gahi	52	72.70	97.05	238.50	2.46	
	Total	131	89.93	176.05	7553.90	42.91	
2020	Groundfish[a]	80	17.04	79.95	14323.13	179.15	77727.54 (20133.68–165424.57)
	D. gahi	59	86.80	112.52	59.15	0.53	
	Total	139	103.84	192.47	14382.28	74.73	
2021	Groundfish	80	16.34	79.48	30457.98	383.20	312118.42 (93792.22–737156.05)
	D. gahi	55	90.64	111.22	373.83	3.36	
	Total	135	106.99	190.70	30831.81	161.68	

[a]An additional one-day transect of four trawls was taken in shallow inshore waters to sample for juvenile toothfish. These four trawls were not included in analyses as their locations were not relevant to the distribution of hoki.

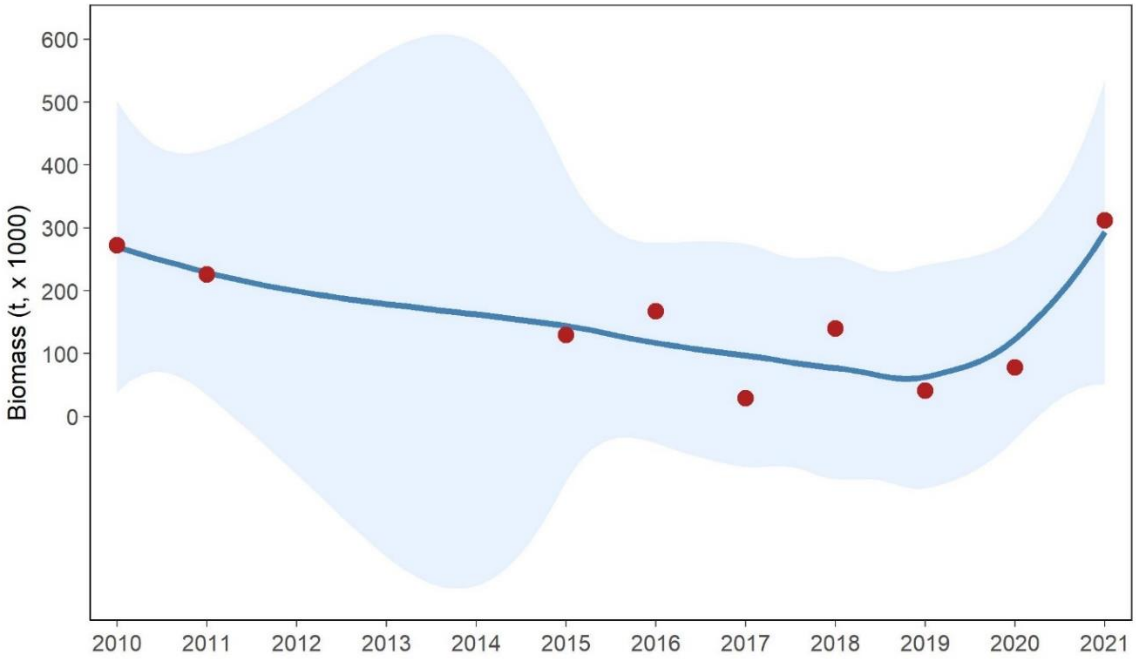

Fig. 5. Hoki biomass estimates (red) and smoothed biomass trend (LOESS; span = 0.75, degree = 2) from summer (February) surveys in Falkland Islands waters. The dark blue line and the light blue area are the LOESS smooth ± 95% confidence intervals.

Winter surveys (July)

The estimated biomass of hoki in the July 2020 survey (41,553 t) was 38% of the biomass estimated in the July 2017 survey (108,207; Table III). However, a total of 27,661 out of 30,000 paired re-samples had higher biomass estimate values in July 2017 than in July 2020 (92.2%), thus not significant at $p > 0.05$. In July 2017, aggregations of hoki were detected to the east and west in the Falkland Islands Conservation Zones, whereas in July 2020 hoki were mainly aggregated to the southwest (Appendix VI). Differences in biomass estimates between February and July surveys are likely due to the migratory pattern of hoki.

Table III. Winter (July) surveys catch and effort, and biomass estimates (mean ± 95% confidence intervals) of hoki 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	6450.40	87.17	108206.57 (27528.30 – 182684.71)
	D. gahi[a]	59	54.70	114	108267.50	949.71	
	Total	133	70.10	188	114717.90	610.20	
2020	Groundfish[b]	33	7.14	33	1721.86	52.15	41552.76 (8229.11 – 65265.20)
	D. gahi	55	98.57	101	232.34	2.29	
	Total	88	105.71	134	1954.20	14.55	

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

ICES Category 5 Total Allowable Catch

Total Allowable Catch (TAC) for the year 2022 under the ICES category 5 assessment framework was set at 6,478 t, as follows:

$$TAC\_5_{2022} = \frac{4408 + 7398 + 7629}{3} = \mathbf{6478}$$

Where the in-zone catch for 2018 (4,408 t), 2019 (7,398 t) and 2020 (7,629 t) excluded experimental (E–licence) and out-of-zone catches (O–licence).

Length analyses

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, were positive (green) in years 2003 and 2013 for females; the rest of the years conservation of immature females was negative (red) or was of concern (yellow). Conservation of immature males was negative or was of concern most years, except for 2013 (green). Indicator $L_{25\%}$/L50, also for conservation of immature fish, showed positive outputs for females at the start of the time series and sporadic positive conservation from 2011 to 2016; most years were of concern. In contrast, conservation of immature males was negative or was of concern most years, including 2019 and 2020. Indicator $L_{max5\%}/L_{\infty}$, for conservation of large individuals, was negative or of concern throughout the time series for females; this indicator was mostly of concern for males with the exception of 2010 (positive) and 2020 (failed). Indicator P_{mega}, for the presence of mega-spawners, was all negative for females and mostly negative for males since 2002. Indicator L_{meanC}/L_{Opt}, for optimal yield, was negative or of concern for females most years. However, L_{meanC}/L_{Opt} for males fluctuated between concerning and positive outputs through the time series, and was negative in 2017 and 2018. Indicator $L_{meanC}/L_{F=M}$, for maximum sustainable yield, was mostly negative for females, with the exception of positive outputs between 2006 and 2015. In contrast, it fluctuated between concerning and positive outputs for males most years, with negative outputs from 2017 to 2020.

Table IV. Female hoki 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	0.99	1.08	0.67	0.00	0.78	0.92
2003	1.04	1.13	0.72	0.02	0.83	0.95
2004	0.86	0.91	0.72	0.02	0.75	0.94
2005	1.00	1.04	0.76	0.04	0.86	0.96
2006	0.82	1.00	0.76	0.03	0.85	1.05
2007	0.95	1.00	0.77	0.05	0.87	0.98
2008	0.91	1.00	0.77	0.04	0.85	0.98
2009	0.86	0.95	0.81	0.07	0.86	1.02
2010	0.78	1.00	0.81	0.09	0.87	1.09
2011	0.92	1.05	0.81	0.11	0.90	1.04
2012	0.97	1.02	0.79	0.05	0.84	0.96
2013	1.07	1.12	0.80	0.08	0.91	0.99
2014	0.89	0.99	0.69	0.01	0.74	0.91
2015	0.86	1.00	0.75	0.04	0.78	1.00
2016	0.97	1.06	0.69	0.00	0.74	0.91
2017	0.69	0.74	0.64	0.00	0.54	0.80
2018	0.85	0.90	0.63	0.00	0.61	0.85
2019	1.02	1.02	0.61	0.00	0.61	0.79
2020	1.04	1.04	0.60	0.00	0.63	0.81

Table V. Male hoki 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	0.92	0.96	0.76	0.03	0.91	0.97
2003	0.97	1.01	0.82	0.12	0.98	1.00
2004	0.81	0.85	0.81	0.08	0.86	0.97
2005	0.94	0.98	0.82	0.15	0.97	0.99
2006	0.73	0.82	0.82	0.12	0.91	1.07
2007	0.91	0.91	0.83	0.13	0.97	1.00
2008	0.87	0.92	0.80	0.08	0.93	0.98
2009	0.84	0.88	0.85	0.11	0.93	1.02
2010	0.75	0.93	0.88	0.19	0.95	1.11
2011	0.85	0.94	0.86	0.22	0.95	1.06
2012	0.91	1.00	0.82	0.13	0.91	0.98
2013	1.05	1.05	0.84	0.16	0.99	0.99
2014	0.88	0.93	0.74	0.02	0.83	0.94
2015	0.89	0.94	0.81	0.10	0.87	1.00
2016	0.95	1.00	0.74	0.03	0.82	0.93
2017	0.67	0.72	0.66	0.00	0.59	0.82
2018	0.83	0.88	0.68	0.01	0.67	0.86
2019	0.99	0.99	0.66	0.01	0.70	0.82
2020	1.01	1.01	0.62	0.00	0.72	0.84

Length-age relationship

The length-age relationship of females and males pooled for the entire time series (n = 5,129) gave the following values: L_∞ = 50.80 cm, k = 0.1132, and t_0 = -2.2064 years. Length and age of females (n = 3,013) ranged from 12 cm to 47 cm, and from 1 year to 16 years, respectively. The length-age relationship of females gave the following values: L_∞ = 53.48 cm, k = 0.1069, and t_0 = -2.2254 years. Length and age of males (n = 2,116) ranged from 12 cm to 43 cm and from 1 year to 15 years, respectively. The length-age relationship of males gave the following values: L_∞ = 43.10 cm, k = 0.1462, and t_0 = -1.9815 years (Appendix VII). Yearly von Bertalanffy parameters are summarized in Appendix VIII. Asymptotic lengths (L_∞) of females fluctuated through the time series, with the LOESS smooth between 40 and 70 cm. For males, asymptotic lengths increased significantly from 2010 to 2018 (Fig. 6).

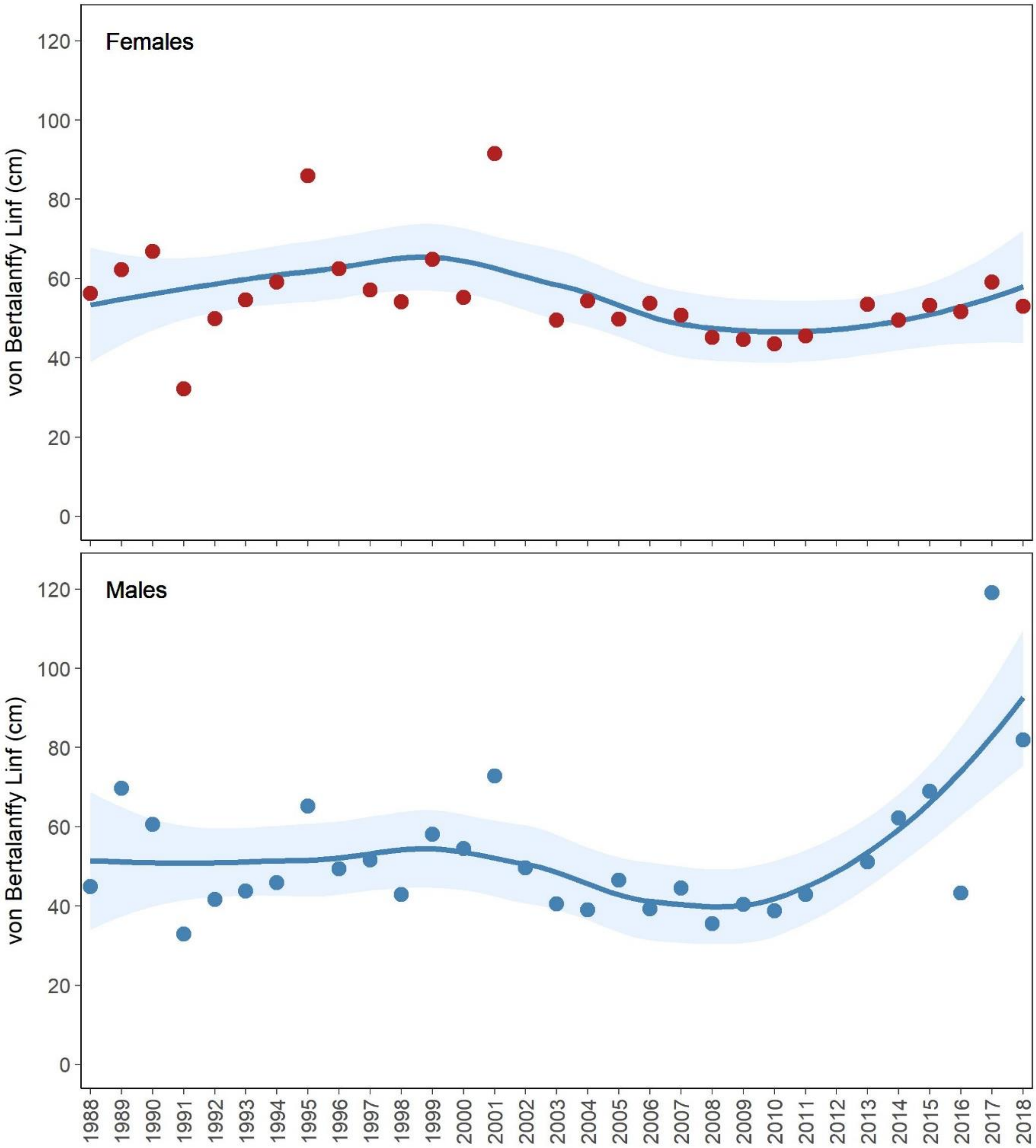

Fig. 6. Asymptotic lengths (L_∞) calculated according to the von Bertalanffy growth function for female and male hoki, 1988 to 2018. Dark blue lines and light blue areas are the LOESS smooths ± 95% confidence intervals. Yearly data correspond to L_∞ in Appendix VIII.

Length at 50% maturity (L50)

Lengths at 50% maturity of females remained relatively stable from 2002 to 2010, and saw a slight decline from 2011 to 2020. Lengths at 50% maturity of males had a declining trend since the year 2002 but this decrease was steeper since 2011 (Fig. 7).

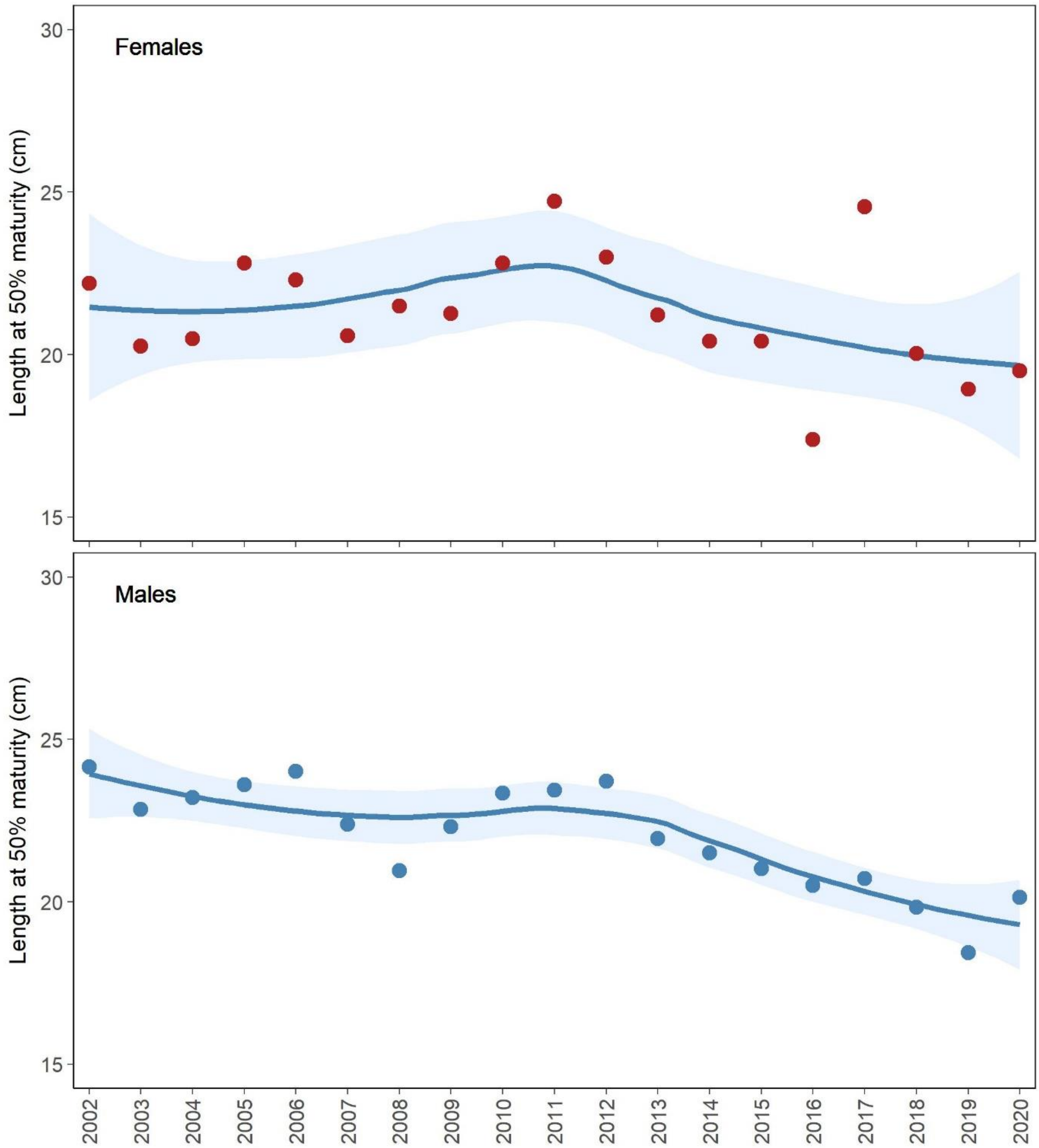

Fig. 7. Lengths at 50% maturity (L50) of female and male hoki, 2002 to 2020. Dark blue lines and light blue areas are the LOESS smooths ± 95% confidence intervals. Yearly data correspond to the L50 intercepts in Appendix IX and Appendix X.

Length frequencies

Female hoki were in the range of sizes from 10 cm to 48 cm pre-anal length, and male individuals were in the range of sizes from 11 cm to 46 cm pre-anal length. Overlap in sizes did not allow certain identification of the total number of cohorts present per year for both, females and males. Individuals > 25 cm pre-anal length and ≥ 4 years old were dominant in 2002–2003, and in 2006–2007. Individuals < 25 cm pre-anal length and < 4 years old were more common in 2004–2005, and from 2007. A peak of nearly 15 cm pre-anal length and 1–year old individuals was observed in 2017. The presence of new cohorts was detected in 2004, 2006, 2010, 2013, and 2017, suggesting recruitment to the fishery of 1– and 2–years old individuals, every 2 to 4 years (Fig. 8; Appendix XI).

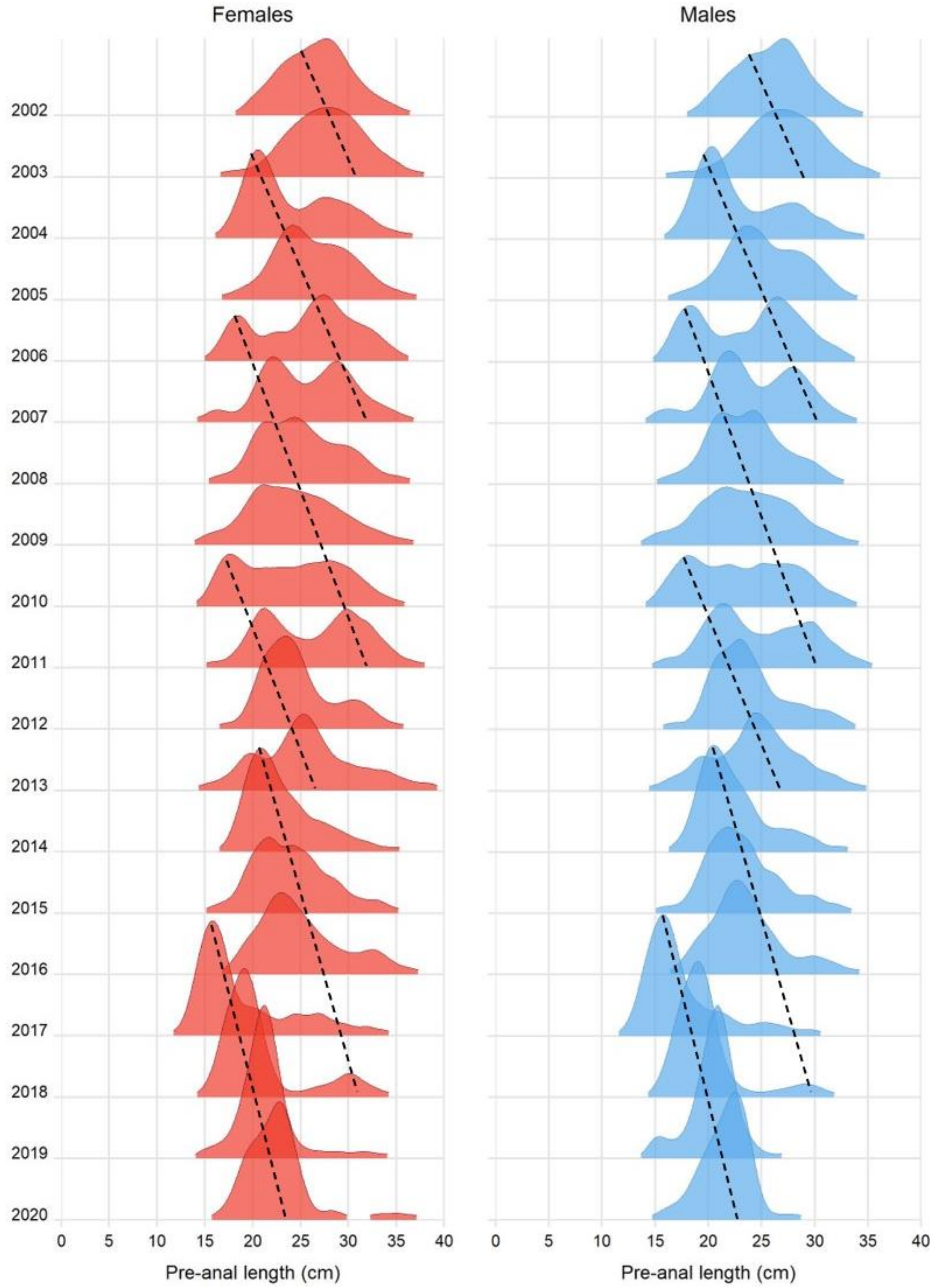

Fig. 8. Length frequency distribution of female and male hoki in Falkland Islands waters. The progression of sizes of the main cohorts through time are indicated by the dotted lines.

Conclusions

The indicator of optimal yield was of concern (yellow) or negative (red) mainly for females through the time series. The MSY indicator was negative since 2016 for females and since 2017 for males; in addition, conservation of immature individuals and large individuals was of concern or negative, and conservation of mega-spawners was negative through the time series. These findings are consistent with declines in length at 50% maturity over the past few years, in particular for males. Length frequency analysis per range of depth, considering the spatial and temporal variability of the presence of hoki may provide greater resolution of length trends. Length Based Indicators suggest that hoki productivity is currently poor; conservation measures should be implemented considering that CPUE has increased substantially in the most recent years. Based on the ICES category 5 assessment framework, a Total Allowable Catch of 6,478 t is recommended for hoki in the year 2022, which represents a decrease of 15% from the total commercial catch in 2020 (7,629 t).

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Appendix

Appendix I. Identifying finfish-licenced observer samples.

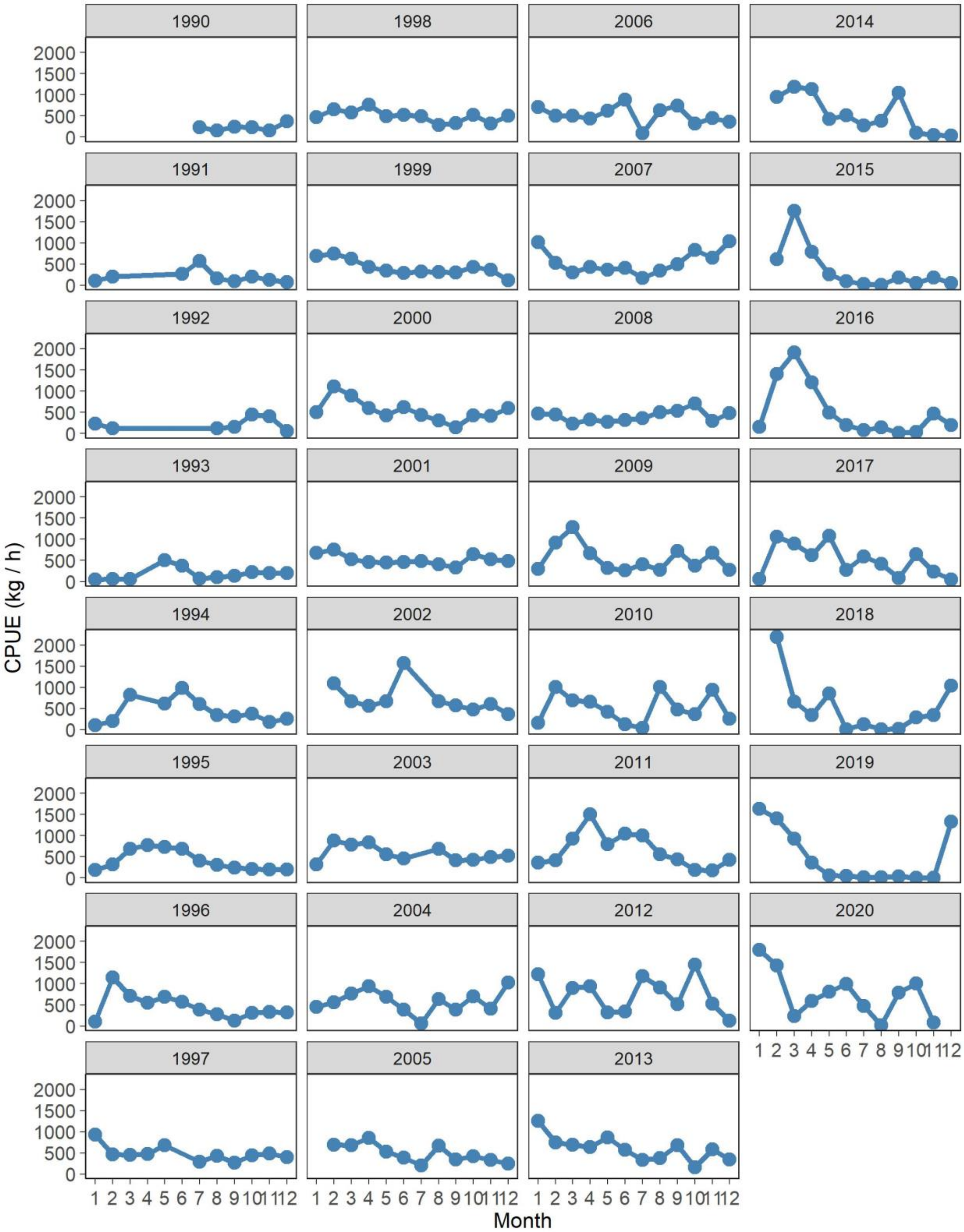
The FIFD observer database identifies samples by vessel, date, activity (fishing gear type), and observer station, but does not directly link to the licence that the vessel was operating under. If required, the licence must be cross-referenced from the catch report. In most cases, a catch report is recorded the same day by the same vessel, and the corresponding licence can be applied to the samples directly. However, in some cases 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.

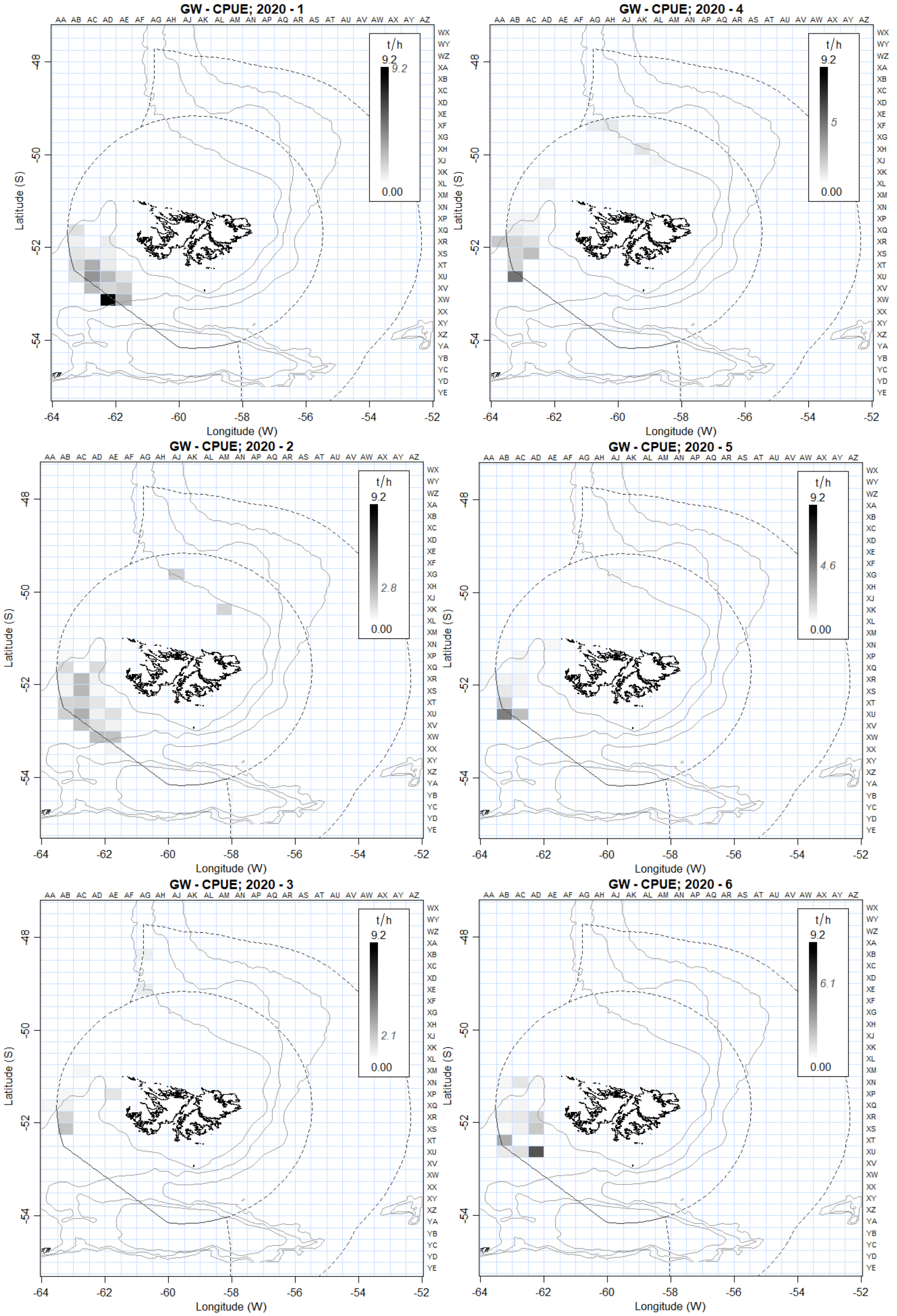
Appendix II. Annual commercial catches (t) of hoki reported in Falkland Islands (excluding E–licence; http://www.fig.gov.fk/fisheries/publications/fishery-statistics; Falkland Islands Government 2021), Argentina (https://www.agroindustria.gob.ar/sitio/areas/pesca_maritima/desembarques/; Sánchez et al. 2012; Navarro et al. 2014, 2019) and Chile (http://www.sernapesca.cl/informes/estadisticas; SERNAPESCA 1990, 2000, 2011, 2021).

Year	Falkland Islands (t)	Argentina (t)	Chile (t)
1987	19,307	782	131,834
1988	12,209	6,952	211,624
1989	13,313	3,085	227,393
1990	7,031	4,353	128,002
1991	4,499	5,583	164,697
1992	14,195	9,534	214,324
1993	8,516	29,174	82,580
1994	10,055	17,472	81,310
1995	15,606	25,228	206,734
1996	13,849	46,241	375,446
1997	13,020	41,787	71,479
1998	22,334	96,218	354,184
1999	18,692	118,356	309,904
2000	19,846	123,926	91,333
2001	19,471	112,539	162,082
2002	26,975	98,865	133,418
2003	23,764	97,797	85,896
2004	25,898	116,965	71,177
2005	16,646	115,340	79,755
2006	19,425	124,638	73,421
2007	16,524	98,808	63,697
2008	15,765	110,269	73,567
2009	23,219	110,717	78,440
2010	19,074	82,855	74,330
2011	22,906	70,903	70,137
2012	15,815	59,595	62,175
2013	16,716	55,966	47,602
2014	7,336	58,396	39,345
2015	6,782	50,469	37,475
2016	11,509	34,946	28,108
2017	3,974	21,930	20,850
2018	4,408	37,598	17,055
2019	7,398	36,038	13,006
2020	7,629	31,239	12,792

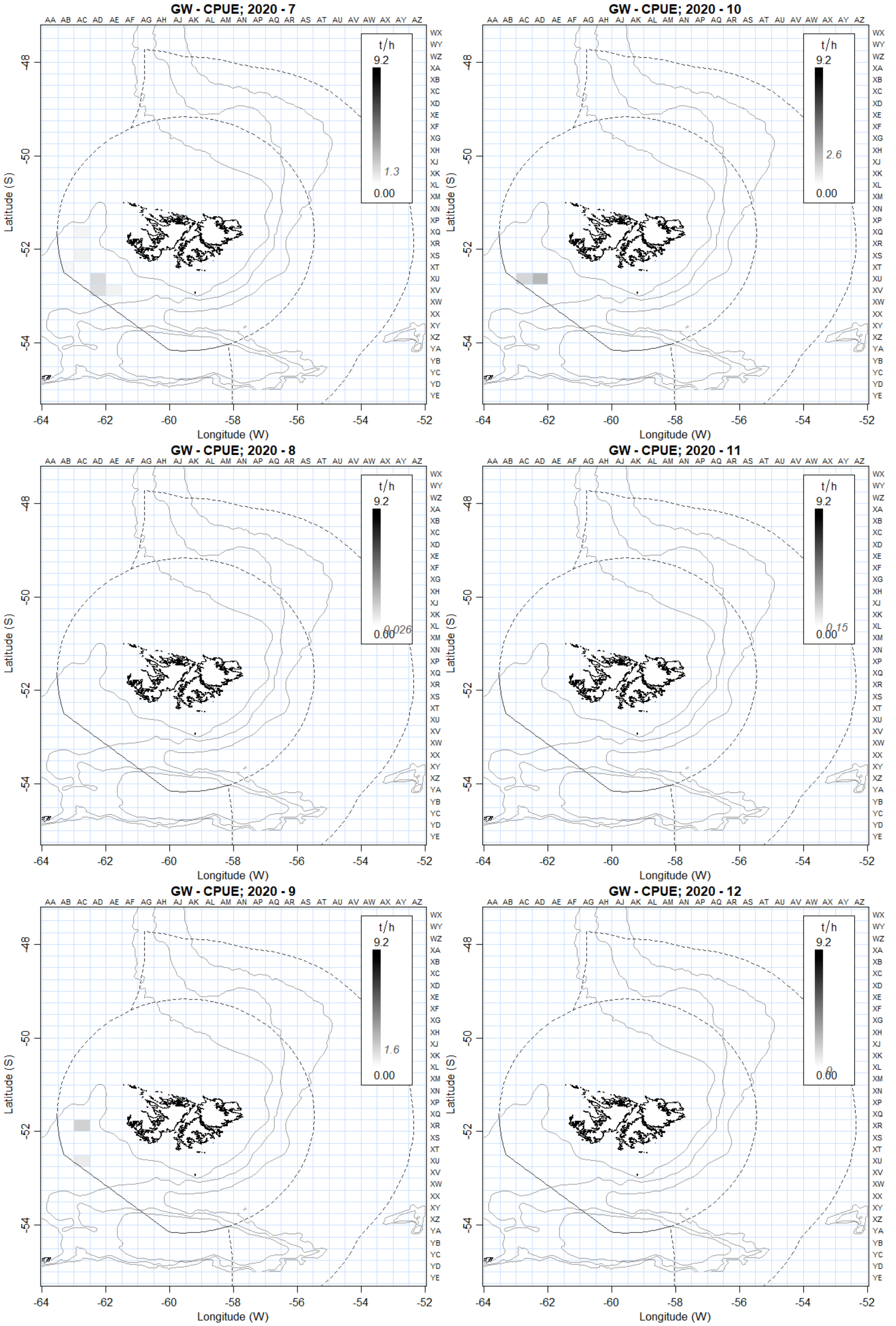
Appendix III. Monthly CPUE of hoki in Falkland Islands waters from 1990 to 2020, estimated from G– and W–licensed vessels.



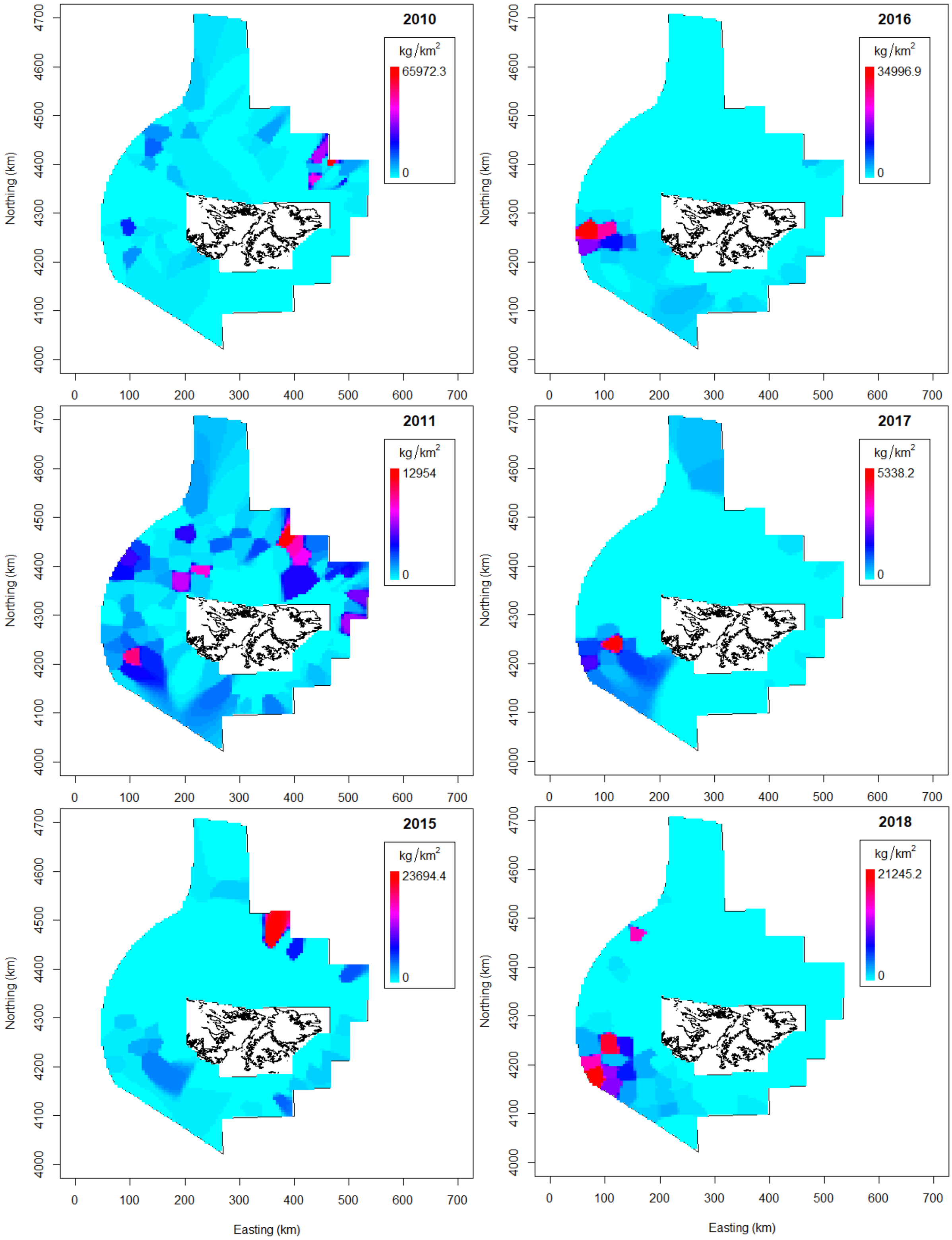
Appendix IV. Monthly CPUE of hoki in Falkland Islands waters during 2020, estimated from G– and W–licensed vessels.



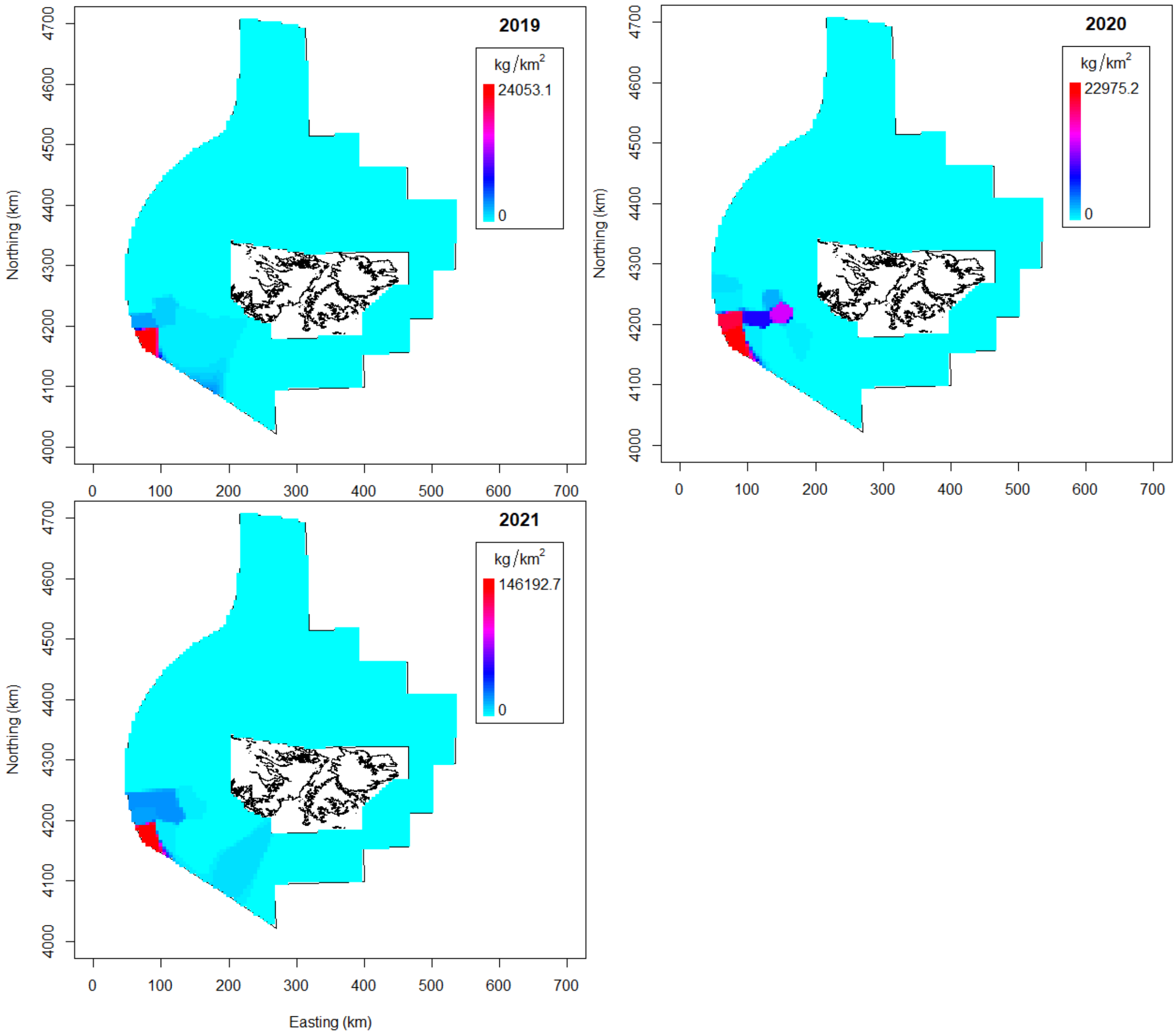
Appendix IV. *continued…*



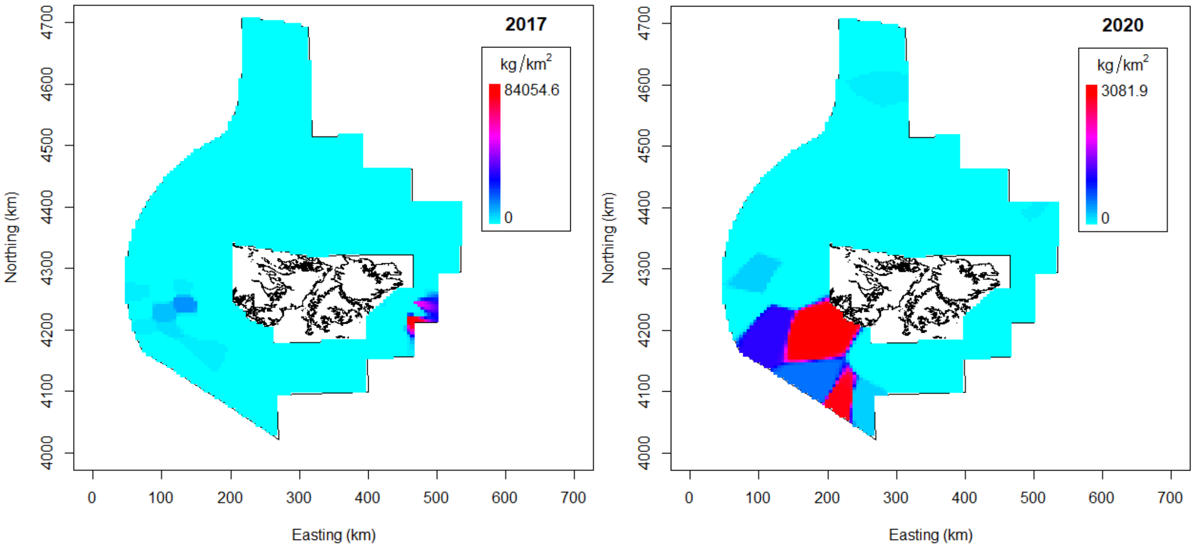
Appendix V. Densities of hoki modelled by inverse distance weighting throughout the Falkland Islands fishing zone, in February 2010–2021.



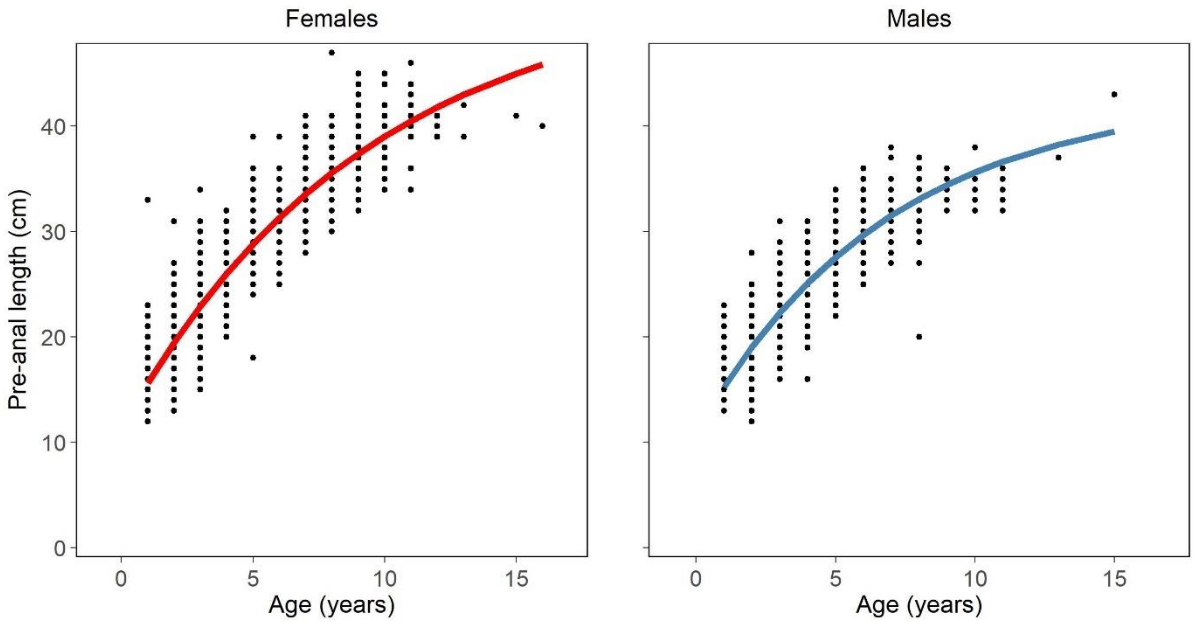
Appendix V. *continued…*



Appendix VI. Densities of hoki modelled by inverse distance weighting throughout the Falkland Islands fishing zone, in July 2017 and July 2020.



Appendix VII. von Bertalanffy age-length relationship of female and male hoki from the Falkland Islands.



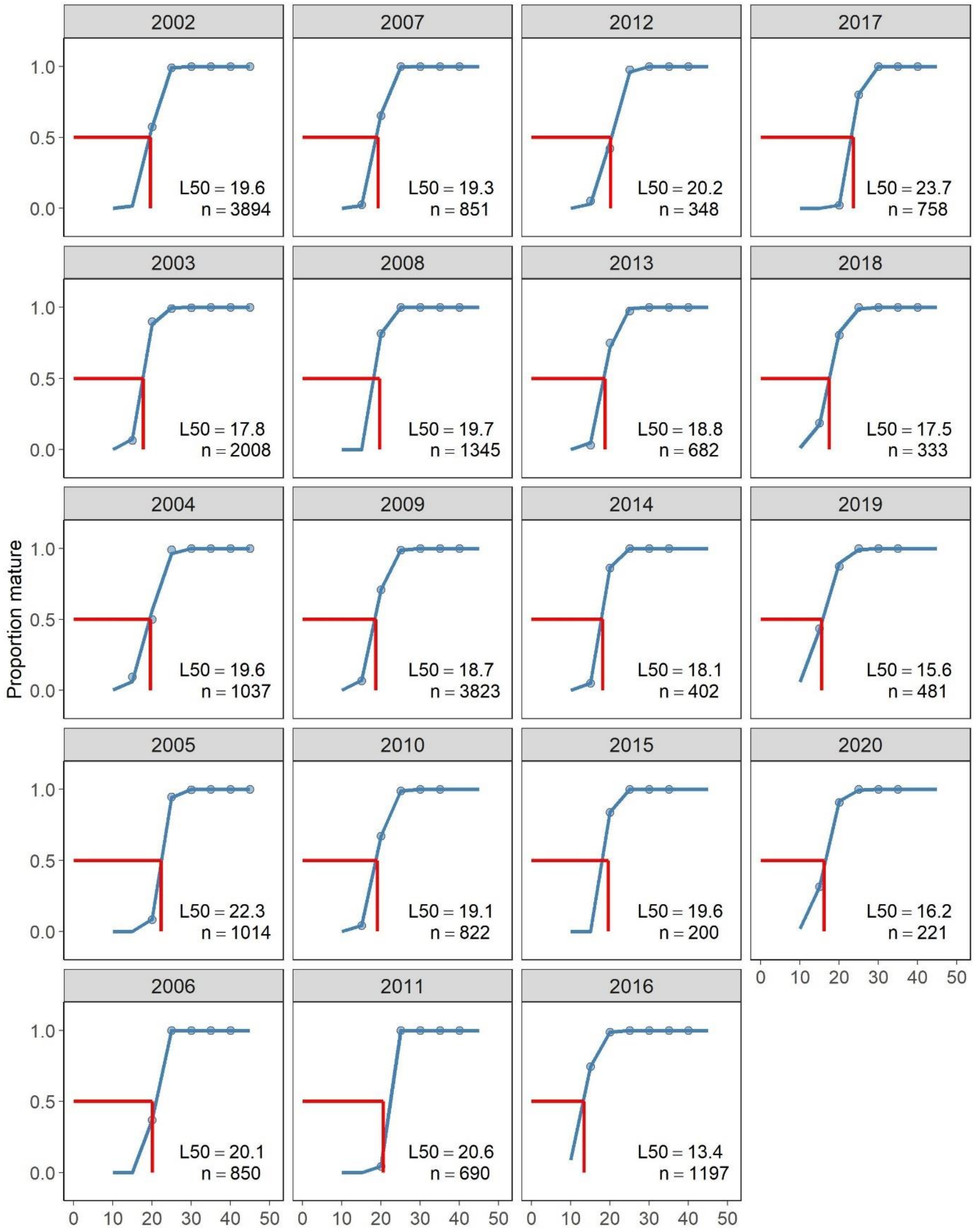
Appendix VIII. Hoki von Bertalanffy length-at-age parameters for curvature (k), age of fish at length zero (t_0), and asymptotic length (L_∞), by year and sex, with 95% confidence intervals.

Sex	Year	N	k		t_0 (years)		L_∞ (cm)	
	1988	1398	0.12	(0.11 - 0.13)	-0.55	(-0.72 - -0.39)	56.24	(54.6 - 58.2)
	1989	299	0.09	(0.07 - 0.1)	-2.16	(-2.76 - -1.65)	62.20	(57.8 - 68.7)
	1990	241	0.08	(0.04 - 0.12)	-2.28	(-3.96 - -1.15)	66.80	(55.1 - 103.1)
	1991	85	1.14	(0.11 - 3.6)	2.39	(-11.88 - 4.16)	32.11	(31.6 - 36.4)
	1992	181	0.13	(0.08 - 0.18)	-2.39	(-3.53 - -1.59)	49.91	(44.8 - 60.3)
	1993	285	0.10	(0.07 - 0.13)	-2.40	(-3.5 - -1.59)	54.57	(49.2 - 64.5)
	1994	437	0.10	(0.08 - 0.12)	-1.27	(-1.87 - -0.77)	59.10	(55.2 - 64.6)
	1995	366	0.04	(0.01 - 0.09)	-4.05	(-7.18 - -1.81)	85.89	(59.7 - 320.5)
	1996	447	0.08	(0.05 - 0.1)	-2.41	(-3.3 - -1.72)	62.49	(55.8 - 74.4)
	1997	391	0.11	(0.09 - 0.12)	-0.78	(-1.12 - -0.48)	57.16	(54 - 61.4)
	1998	263	0.13	(0.11 - 0.16)	-0.37	(-0.8 - -0.03)	54.08	(50.7 - 58.9)
	1999	384	0.08	(0.06 - 0.11)	-1.97	(-2.79 - -1.31)	64.81	(58 - 76.9)
	2000	151	0.11	(0.08 - 0.14)	-1.60	(-2.36 - -1)	55.22	(50.8 - 62.2)
	2001	401	0.04	(0.02 - 0.06)	-4.78	(-6.08 - -3.81)	91.57	(70.3 - 164.7)
	2002	407	0.01	(0 - 0.05)	-5.86	(-6.74 - -4.13)	213.07	(79.8 - 1021.3)
F	2003	298	0.13	(0.1 - 0.15)	-2.19	(-2.68 - -1.79)	49.47	(45.8 - 54.8)
	2004	354	0.09	(0.05 - 0.13)	-3.05	(-4.1 - -2.27)	54.35	(46.1 - 73.6)
	2005	292	0.14	(0.09 - 0.2)	-1.35	(-2.45 - -0.58)	49.73	(45 - 59.4)
	2006	258	0.12	(0.06 - 0.17)	-1.66	(-2.56 - -1.03)	53.74	(45.4 - 75.8)
	2007	511	0.11	(0.08 - 0.14)	-2.56	(-3.25 - -1.99)	50.79	(45.8 - 58.7)
	2008	454	0.17	(0.13 - 0.22)	-1.07	(-1.7 - -0.58)	45.12	(41.6 - 50.8)
	2009	499	0.17	(0.14 - 0.19)	-0.88	(-1.2 - -0.6)	44.58	(42.4 - 47.3)
	2010	392	0.17	(0.13 - 0.21)	-0.89	(-1.3 - -0.56)	43.57	(40.5 - 47.9)
	2011	243	0.19	(0.16 - 0.23)	-1.08	(-1.55 - -0.7)	45.53	(43.3 - 48.6)
	2012	0	NA	(NA - NA)	NA	(NA - NA)	NA	(NA - NA)
	2013	343	0.12	(0.08 - 0.15)	-1.99	(-2.69 - -1.45)	53.46	(48.3 - 62.5)
	2014	237	0.14	(0.08 - 0.19)	-1.53	(-2.31 - -0.99)	49.50	(42.6 - 65.5)
	2015	383	0.13	(0.09 - 0.16)	-1.19	(-1.7 - -0.78)	53.20	(48 - 61.9)
	2016	371	0.14	(0.1 - 0.18)	-1.10	(-1.65 - -0.66)	51.68	(46.2 - 61.2)
	2017	278	0.09	(0.06 - 0.12)	-1.75	(-2.28 - -1.33)	59.16	(50.9 - 75.7)
	2018	262	0.12	(0.08 - 0.16)	-1.70	(-2.46 - -1.14)	53.05	(46.8 - 65.6)

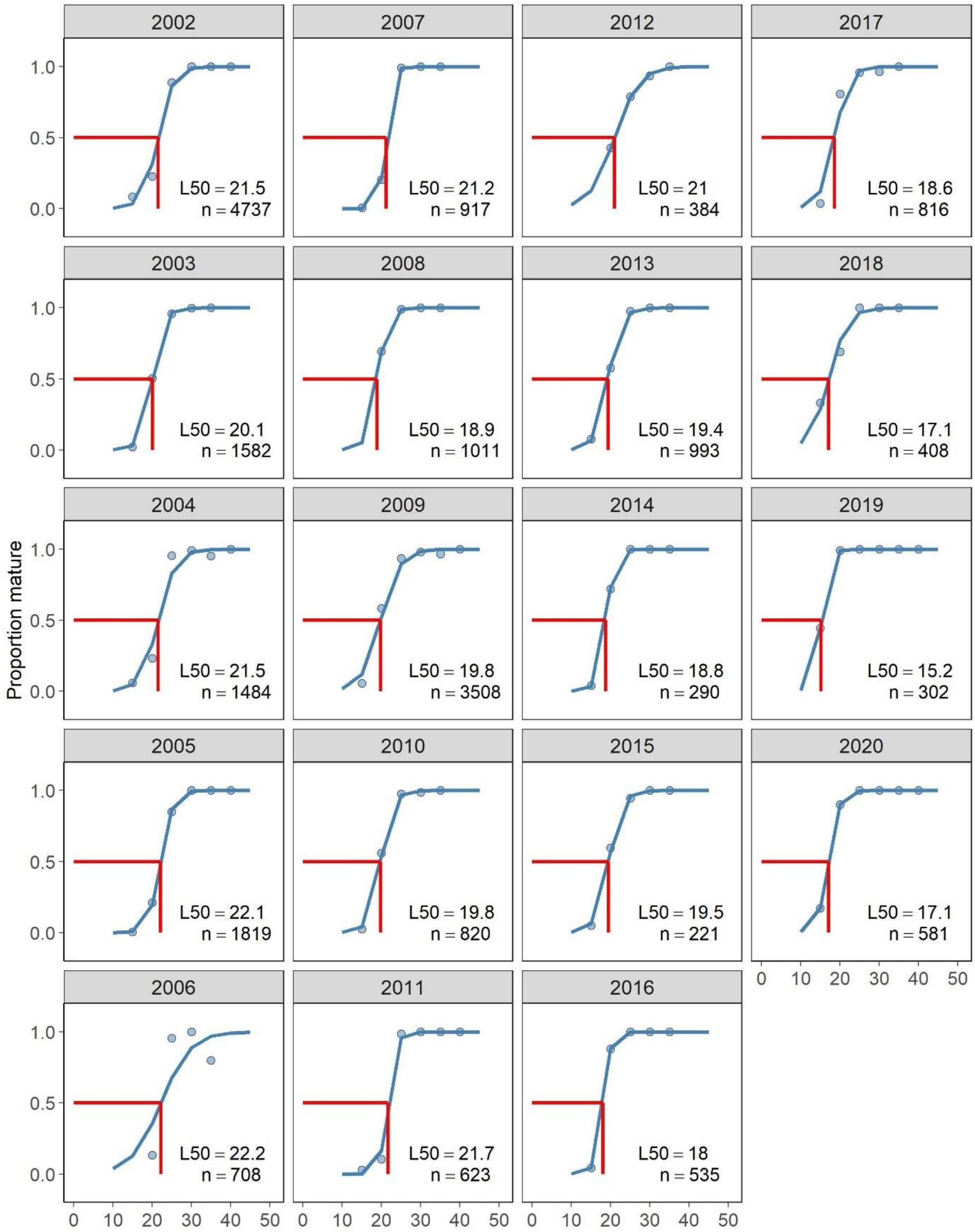
Sex	Year	N	k		t_0 (years)		L_∞ (cm)	
	1988	1031	0.20	(0.18 - 0.22)	0.15	(-0.02 - 0.33)	44.82	(43.4 - 46.4)
	1989	199	0.06	(0.04 - 0.09)	-3.16	(-4.29 - -2.32)	69.74	(58.5 - 97.1)
	1990	141	0.08	(0.03 - 0.14)	-2.51	(-4.69 - -1.23)	60.55	(49.5 - 108.2)
	1991	59	0.57	(0.09 - 1.61)	0.90	(-11.89 - 3.41)	32.97	(31.9 - 39)
	1992	166	0.20	(0.15 - 0.26)	-1.63	(-2.46 - -1.01)	41.62	(39.2 - 45.4)
	1993	292	0.15	(0.1 - 0.2)	-2.06	(-3.32 - -1.2)	43.81	(40.4 - 50.5)
	1994	133	0.15	(0.1 - 0.2)	-0.88	(-2.07 - -0.09)	45.91	(41.9 - 54)
	1995	201	0.06	(0.01 - 0.13)	-4.20	(-8.48 - -1.44)	65.19	(47 - 268.9)
	1996	390	0.12	(0.08 - 0.15)	-1.76	(-2.76 - -1.01)	49.40	(45.2 - 56.9)
	1997	232	0.13	(0.11 - 0.16)	-0.49	(-0.83 - -0.19)	51.57	(47.5 - 57.3)
	1998	135	0.20	(0.14 - 0.28)	-0.03	(-0.63 - 0.46)	42.89	(38.6 - 49.2)
	1999	194	0.09	(0.04 - 0.14)	-2.13	(-4.13 - -1.03)	58.06	(48.8 - 95.9)
	2000	65	0.11	(0.04 - 0.18)	-1.49	(-3.64 - -0.27)	54.54	(45.5 - 91.6)
	2001	258	0.04	(0.02 - 0.07)	-6.14	(-8.16 - -4.69)	72.85	(55.7 - 139.9)

	2002	279	0.10	(0.06 - 0.14)	-3.11	(-4.38 - -2.21)	49.63	(42.9 - 65.1)
M	2003	198	0.18	(0.14 - 0.22)	-1.64	(-2.16 - -1.22)	40.56	(37.6 - 45)
	2004	285	0.16	(0.09 - 0.24)	-2.76	(-4.24 - -1.8)	38.97	(34.8 - 49.3)
	2005	67	0.16	(0.1 - 0.23)	-1.13	(-2.24 - -0.38)	46.54	(41 - 58.1)
	2006	144	0.22	(0.1 - 0.34)	-1.06	(-2.38 - -0.32)	39.32	(34.2 - 55.4)
	2007	414	0.14	(0.1 - 0.18)	-1.82	(-2.46 - -1.32)	44.50	(40.3 - 51.6)
	2008	286	0.27	(0.18 - 0.37)	-0.71	(-1.52 - -0.14)	35.49	(32.8 - 40.2)
	2009	360	0.19	(0.15 - 0.23)	-0.89	(-1.34 - -0.52)	40.34	(37.7 - 44)
	2010	260	0.20	(0.15 - 0.25)	-0.98	(-1.5 - -0.55)	38.73	(35.9 - 43.1)
	2011	130	0.17	(0.11 - 0.23)	-1.79	(-2.69 - -1.15)	42.92	(38.6 - 50.7)
	2012	0	NA	(NA - NA)	NA	(NA - NA)	NA	(NA - NA)
	2013	177	0.12	(0.07 - 0.17)	-1.84	(-2.67 - -1.24)	51.18	(44 - 66.8)
	2014	167	0.08	(0.01 - 0.16)	-2.84	(-4.39 - -1.69)	62.18	(42 - 260.6)
	2015	294	0.08	(0.02 - 0.13)	-1.98	(-3.12 - -1.21)	68.92	(50.3 - 178)
	2016	252	0.17	(0.11 - 0.23)	-1.09	(-1.76 - -0.57)	43.30	(38.5 - 52)
	2017	226	0.04	(0.01 - 0.09)	-1.88	(-2.39 - -1.31)	119.04	(62.5 - 691.4)
	2018	177	0.05	(0.01 - 0.11)	-3.00	(-4.4 - -1.86)	81.93	(52.6 - 371.8)

Appendix IX. Binomial logistic regressions of juvenile (0) or adult (1) maturity vs. length for female hoki. Red lines: Length intercept of 50% adulthood, corresponding to Fig. 7.



Appendix X. Binomial logistic regressions of juvenile (0) or adult (1) maturity vs. length for male hoki. Red lines: Length intercept of 50% adulthood, corresponding to Fig. 7.



Appendix XI. Number of hoki individuals sampled for length frequency distributions.

Year	Females (n)	Males (n)
2002	11,626	8,650
2003	3,713	2,608
2004	5,408	4,181
2005	6,000	4,378
2006	3,383	2,243
2007	4,563	3,158
2008	4,449	3,090
2009	9,677	7,476
2010	2,875	2,058
2011	1,503	1,135
2012	1,957	1,289
2013	2,749	1,737
2014	1,460	905
2015	746	588
2016	3,213	1,713
2017	1,273	1,253
2018	1,814	1,475
2019	1,372	996
2020	1,514	1,076