PRELIMINARY ANALYSIS OF THE VARIABILITY IN THE LENGTH-WEIGHT RELATIONSHIP OF INDIAN OCEAN ALBACORE

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Abstract

We collated a data set of almost half a million observations of fork length and round weight for albacore spanning more than two decades and spreading across the fishing grounds of albacore over the whole Indian Ocean. Most data were collected on fresh fish at sea on large-scale longliners. First, we fitted generalized additive models that showed that the relationship between length and weight varied with sex, space, and time while the fleet and fishery also had an effect on morphometric parameters of Indian Ocean albacore. Secondly, we used linear models to develop statistical relationships between fork length and round weight for operational use and showed that the large areas used for deriving albacore abundance indices for the assessment had a significant effect to explain the observed variability in weights, although the percentage of variation was very small. Weights predicted in the northeastern part of the Indian Ocean were found to be higher than in other regions. Finally, fitting a univariate linear model only considering fork length as covariate showed that the relationships used for the assessments conducted in 2019 and 2022 overestimated albacore weight at length.

Keywords: morphometrics, fisheries observer programs, regional observer scheme, tuna fisheries

Introduction

Morphometric relationships and conversion factors are instrumental in fisheries science to harmonize size-frequency data and compute weight from length so as to derive raising factors for extrapolation, estimate the species composition of the catch from size-frequency samples, and compute reporting coverage for catches reported in numbers. The current IOTC official relationship between fork length (FL) and round weight (RD) for Indian Ocean albacore (*Thunnus alalunga*) has been derived from fish sampled between 1990 and 1991 from the large-scale drifting gillnet fishery that operated in the south-central Indian Ocean (Hsu 1999). Meanwhile, the relationship used in the last stock assessment in 2019 was based on albacore caught in the southeast Atlantic Ocean in the early 1990s (Penney 1994). During the last Working Party on Temperate Tuna (WPTmT07(AS)), Kitakado et al. (2019) developed an alternative relationship based a large data set of data collected by scientific observers onboard Japanese longliners during 2012-2016 that predicts lower overall fish weights (by 10-15%) compared to Penney (1994) and was used for sensitivity analysis runs of the model (Langley 2019). Since then, several morphometric data have been collected for albacore through different fisheries monitoring programs and research projects conducted in the Indian Ocean (Setyadji et al. 2012; Dhurmeea et al. 2016; Bodin et al. 2018; Bonhommeau et al. 2019).

In this context, the overarching objective of the study was to develop a statistical relationship between fork length and round weight for albacore based on the collation of different data sources available from a range of fisheries catching albacore across the whole Indian Ocean. First, we assessed the factors affecting the variability in weight measurements with generalized additive models (Hastie and Tibshirani 1990). Second, we fitted mean regression models to the data and assessed the influence of spatio-temporal factors, sex, fishery, and fleet on the weights solely predicted from fish length.

Materials & Methods

Albacore morphometric data were collated from different sources and harmonized according to a common standardized format (**Table 1**). The original data sets were collected as part of (i) historical longline observer programs from Korea and the UK (IOTC 2005; Geehan and Pierre 2013), (ii) the Japan national scientific observer program for longliners for which data were submitted in electronic format to the Secretariat as part of the IOTC Regional Observer Scheme (ROS), (iii) the pelagic longline observer programs from China and Taiwan,China, (iv) research projects conducted on albacore by the University of Mauritius (UoM) and the French national Research Institute for Sustainable Development (IRD) (Dhurmeea et al. 2016; Bodin et al. 2018), and (v) routine monitoring program on the biology of large pelagics conducted by the French national research institute Ifremer in Reunion Island (Bonhommeau et al. 2018, 2019) (**Fig. 2**).

Observer data from Chinese longliners were filtered based on the visual exam of the scatterplots between fork length and round weight for each trip as some weight measurements were made visually by some observers. A more thorough quality and control procedure was applied to select the good-quality observer data collected onboard Taiwanese longliners. The spatial resolution considered for the study was a grid of 5x5-degree squares although the spatial information was larger for 48 samples collected at sea in the Chagos archipelago and 70 samples collected from the semi-industrial longline fishery based in Reunion Island.

The very few fish larger than 130 cm fork length (i.e., n = 8) were removed from the analysis. After filtering the data, the total data set was comprised of 481,564 albacore caught between 2000 and 2021 from longline, baitboat, line, and purse seine fisheries (**Table 2**). The sampling design was unbalanced with most of the data having been collected by scientific observers deployed on commercial large-scale longliners that contributed to 99.7% of the total data set. Samples from fresh fish caught by Taiwanese, Japanese, and Chinese longliners represent the very large majority of the observer data available for the study. In the case of Japanese data, measurements of fork length were taken to the nearest 0.1 cm with tape, caliper and/or measuring board and round weights were mostly taken with 150 kg platform scales and beam scales and reported to the nearest 0.1 kg (*pers. com.* T. Nishida). Less information is available on the protocol used by observers in other longline fisheries.

Other morphometric measurements for albacore caught with purse seine (n = 871), longline (n = 430), and pole and line (n = 302) were collected in processing factories located in Victoria (Seychelles), Le Port (La Réunion), Port Louis

(Mauritius), and Cape Town (South Africa) as part of monitoring and research projects conducted in the region between 2009 and 2018 (Chassot et al. 2014; Dhurmeea et al. 2016; Bodin et al. 2018; Bonhommeau et al. 2018). In addition, some samples (n = 185) were directly collected in the field for fish caught in coastal handline and trolling fisheries and landed in some local markets of Mauritius (Dhurmeea et al. 2016). Information on fish gender was not collected by most observers at sea while it was generally recorded for samples collected in processing factories and landing sites. In total, the sex (i.e., male, female, or indeterminate) was available for 11,560 fish, i.e., 2.4% of all samples.

Statistical models

Generalized additive models

GAMs were used to examine the factors susceptible to affect the relationship between albacore size and weight. Length and weight data were log10-transformed to stabilize the variance. Year (YEAR) and month (MONTH) were included in the models to represent potential annual and seasonal changes in the relationship, e.g., due to changes in prey availability and environmental conditions over time. A tensor product smooth of the longitude (LON) and latitude (LAT) of the centroids of the areas (5x5-degree squares in most cases) was used to model the spatial autocorrelation in the data. Differences between gender were tested by including SEX as a categorical covariate as well as in interaction with fork length and the 2-dimensional tensor product of longitude and latitude. FISHERY and FLEET were finally included as categorical covariates in the models to account for differences in fishery catchability linked for instance to gear configuration as well as differences in sampling protocols.

Different models of increasing complexity were built and the best model was selected based on the Akaike Information Criterion (AIC):

$$\log_{10}RD_i = s(\log_{10}FL_i) + te(LON, LAT) + YEAR + s(MONTH) + \epsilon_i \qquad (1)$$

$$\log_{10}RD_i = s(\log_{10}FL_i) + te(LON, LAT) + YEAR + s(MONTH) + SEX + \epsilon_i \qquad (2)$$

$$\log_{10}RD_i = SEX + s(\log_{10}FL_i{:}SEX) + te(LON, LAT) + YEAR + s(MONTH) + \epsilon_i \qquad (3)$$

$$\log_{10}RD_i = SEX + s(\log_{10}FL_i{:}SEX) + te(LON, LAT){:}SEX + YEAR + s(MONTH) + \epsilon_i \qquad (4)$$

$$\log_{10}RD_i = SEX + s(\log_{10}FL_i{:}SEX) + te(LON, LAT){:}SEX + YEAR + s(MONTH) + FISHERY + FLEET + \epsilon_i \qquad (5)$$

where *i* indicates each fish and s() represents non-parametric smoothing terms. Model residuals ϵ were assumed to be independent and identically distributed following a random variable of Gaussian distribution with mean zero and constant variance. Model fitting and the automatic selection of degrees of freedom for the regression splines were performed using the generalized cross-validation method (Wood 2011). Assumptions of homoscedasticity and Gaussian distribution were checked through the residuals.

Mean linear regression models

We used mean linear regression models to derive a univariate relationship for predicting round weight from observations of fork length and then assessed the influence of other factors on weight predictions. In addition to fork length (FL), we included the following categorical covariates in the model: gender (SEX), year of capture (YEAR), month of capture (MONTH), CPUE area (AREA), fishery (FISHERY), and fishing fleet (FLEET). Interactions between sex and size, sex and area, and area and size were included in the model. The full model fitted to the morphometric data was:

$$\log_{10}(RD_i) = \log_{10}(FL_i) + AREA + SEX + YEAR + FISHERY + MONTH + FLEET + \log_{10}(FL_i){:}SEX + AREA{:}log10FL + AREA{:}SEX + \epsilon_i \qquad (6)$$

The model residuals ϵ_i were assumed to be independent and identically distributed normal random variables with mean zero and constant variance. We log10-transformed the variables to represent the assumption that measurement errors in weights are multiplicative. Predictions of the parameters accounted for bias due to log10-transformation (Smith 1993). Assumptions of homoscedasticity and Gaussian distribution were checked through the residuals. The best model was selected from stepwise regression analysis based on the Akaike information criterion (AIC). Statistical analyses were performed in R version 4.1.0 (R Core Team, 2022).

Results

Non-linear models

The GAM including all covariates (Eq. (5)) had the lowest AIC and explained most of the variability in the observed weights (**Table 3**). The total deviance explained was 91.4%. Results showed that the relationship between fork length and round weight varies with sex, space, and time while the fleet and fishery have also an effect on morphometric parameters of Indian Ocean albacore (*p*-value< 0.001). The relationship shows some seasonal variations with the highest values of weight estimated in February-March and the lowest values in August (**Fig. 3**). The interaction between fork length and sex indicates that the relationship differs between males and females (**Fig. 4**). Habitat explains some variability in the relationship, with increased weight at higher latitudes and some variability along the coasts of the Indian Ocean (**Fig. 5**). Diagnostic plots are given in Appendix I and show some departure from the assumption of normality at the extremes, due to some variation in weight at length for very small and large fish, associated with sparse data (**Fig. 8**).

Linear models

The linear model including all covariates except fishery had the lowest AIC. All effects kept in the model were found to be highly statistically significant. However, each of them explained a small percentage of total variation as compared to fork length. After accounting for length, the most important effect explaining weight was the area of origin of the fish (**Table 4**). The relationship was also found to vary with sex, with males having smaller weights than females.

The model including fork length and area as covariates explained 89.7% of the deviance in the data. The effect of area was highly significant but explained only 0.34% of the total percentage of variation in the data. Weights predicted in area 2 were higher than in the other areas while predicted in areas 3 and 4 were very similar and the lowest (**Fig. 6**).

The model fitted to the overall data set that only considered fork length as covariate predicted lower weights at length than the relationship of Penney (1994) used in the stock assessment model in 2019 (**Fig. 7**). The relationship was however very similar to the one derived by Kitakado et al. (2019) and used in the stock assessment in 2022 for the size range 50-90 cm, while it diverged from above 90 cm to predict smaller weights at larger sizes (**Fig. 7** and **Table 5**).

Discussion & perspectives

We collated a data set of almost half a million observations of fork length and round weight of albacore spanning more than two decades and spreading across the fishing grounds of albacore over the whole Indian Ocean. Data were collected with different protocols and most measurements were made on fresh fish at sea on longliners. Little information is available on the tools used to measure weight but ship motions at sea are known to affect the precision of weights measurements while initial data mining indicated that some weight data were inconsistent and possibly visually estimated by the observers. Stricter rules could be adopted to filter the data (e.g., based on Cook's distance) and remove the samples collected in the Atlantic Ocean regarding the large size of the data set in future analyses

Including random effects in the GAMs would be useful to better account for co-dependence within samples (Chang et al. 2022). As part of this preliminary analysis, attempts were made to fit a random effect and allow the sampling strata (i.e., combination of year, month, latitude, longitude, and fleet) to affect the estimates of intercept terms but computation time was very long due to the large sample size. Sub-sampling the data set within each stratum might be a good way forward while an alternative statistical and estimation approach to account for the non-linear effects in the relationship could be envisaged (Kristensen et al. 2016).

Acknowledgments

We are grateful to all observers, samplers, and staff involved in the collection and curation of the data used in the present analysis.

Tables

Table 1: Definition of the fields included in the albacore morphometric data set

Field	Definition
FISH_IDENTIFIER	Unique identifier of the fish
SOURCE	Institution of origin of the data
PROJECT	Project during which the fish was sampled
FLEET_CODE	IOTC code for the fleet
FLEET	IOTC label for the fleet
FISHERY_GROUP_CODE	IOTC code for the fishery group
FISHERY_GROUP	IOTC label for the fishery group
FISHERY_CODE	IOTC code for the fishery
FISHERY	IOTC label for the fishery
FISHING_GROUND_CODE	CWP grid code or area name when not available
GEOM_WKT	Well-known text of the geometry
LON_CENTROID	Longitude (decimal degrees) of the centroid of the fishing ground
LAT_CENTROID	Latitude (decimal degrees) of the centroid of the fishing ground
CAPTURE_DATE_START	Minimum date of capture of the fish (YYYY-MM-DD)
CAPTURE_DATE_END	Maximum date of capture of the fish (YYYY-MM-DD)
CAPTURE_QUARTER	Quarter of the "average" date of capture: 1, 2, 3, 4
SAMPLING_PLATFORM	Platform where the fish was sampled: Factory, Field, Lab or Onboard
SPECIES_CODE	ASFIS code. ALB = albacore
SAMPLING_STATUS	Status of the fish at sampling: Fresh or Defrosted
SEX	Sex of the fish derived from macroscopic exam. M = Male; F = Female; I = Indeterminate; U = Unknown
FL	Fork length (cm)
RD	Round weight, i.e., body mass of the fish (kg)
log10FL	Logarithm to base 10 of fork length
log10RD	Logarithm to base 10 of round weight

Table 2: Number of albacore samples (N) by data source, fleet, and fishery group along with the range of morphometric measurements for fork length (FL; cm) and round weight (RD; kg). OFDC = Overseas Fisheries Deveopment Council; SHOU = Shanghai Ocean University; UoM-IRD = University of Mauritius - Institut de Recherche pour le Développement

Source	Fishery group	Fleet	N	FL	RD
IOTC HISTORICAL	Longline	Japan	8	95-112	15-35
	Longline	Not elsewhere included	14	103-115	17-34
	Longline	Republic of Korea	434	66-117	3-30
	Longline	Taiwan,China	26	99-118	20-35
IOTC ROS	Longline	Japan	28,165	51-128	2-35
Ifremer	Longline	EU,Reunion	70	93-112	17.4-31.1
OFDC	Longline	Taiwan,China	438,558	60-130	2-36
SHOU	Longline	China	12,571	58-126	5-35
UoM-IRD	Longline	EU,Reunion	236	88-112	12.8-27.8
	Longline	Taiwan,China	124	89-116	16.4-31.2
	Purse seine	EU,France	359	83-108	14.1-30.4
	Purse seine	EU,Italy	156	83-112	14.1-33.1
	Purse seine	EU,Mayotte	62	89-108	18.3-29.6
	Purse seine	EU,Spain	24	93-109	17.4-29.8
	Purse seine	Seychelles	270	85-112	15.3-33.1
	Line	Mauritius	138	89-112	17.1-28.6
	Line	South Africa	47	58-114	4.2-28.1
	Baitboat	South Africa	302	67-112	5.4-28.1

Table 3: Estimates of degrees of freedom (df) and values of Akaike Information Criterion (AIC) for the five Generalized Additive Models fitted to the fork length and round weight data of Indian Ocean albacore

Model	df	AIC
GAM1	90.59045	-805,350.1
GAM2	93.48680	-811,632.6
GAM3	99.93244	-813,308.8
GAM4	147.98552	-816,016.5
GAM5	173.33077	-816,414.2

Table 4: Summary table of analysis of variance of the round weight of Indian Ocean albacore for the best linear model selected based on the lowest AIC. df = degrees of freedom

Source of variation	df	Mean squares	Percentage of variation	F statistic	p-value
log10FL	1	10,080.781	89.39	4,803,306.4	<0.001
SA_AREA_CODE	4	9.664	0.34	4,604.5	<0.001
SEX	3	6.310	0.17	3,006.6	<0.001
YEAR	17	5.003	0.75	2,383.8	<0.001
MONTH	11	0.868	0.08	413.7	<0.001
FLEET_CODE	10	2.135	0.19	1,017.1	<0.001
log10FL:SA_AREA_CODE	4	2.947	0.10	1,404.4	<0.001
log10FL:SEX	3	0.352	0.01	167.6	<0.001
Residuals	481,510	0.002	8.96		

Table 5: Weights (kg) predicted for a range of fork lengths (50-130 cm) based on the mean linear regression model fitted to all data with only fork length as covaruate (This study), the relationships used in the stock assessments (SA) performed in 2019 (Penney 1994) and 2022 (Kitakado et al. 2019), and the mean linear regression model including both fork length and areas used for CPUE analyses

Fork length	PRESENT STUDY	SA 2019	SA 2022	IRALB01	IRALB02	IRALB03	IRALB04	IRALB05
50	2.17	2.51	2.09	2.50	2.51	2.33	2.32	2.45
60	3.84	4.41	3.77	4.31	4.33	4.02	4.01	4.23
70	6.22	7.11	6.19	6.84	6.87	6.38	6.36	6.72
80	9.46	10.76	9.53	10.20	10.25	9.51	9.48	10.02
90	13.67	15.49	13.93	14.51	14.58	13.54	13.49	14.25
100	19.02	21.47	19.57	19.90	19.99	18.56	18.50	19.54
110	25.63	28.85	26.61	26.47	26.59	24.69	24.61	25.99
120	33.66	37.77	35.24	34.35	34.51	32.03	31.93	33.73
130	43.25	48.40	45.62	43.65	43.85	40.71	40.58	42.86

Figures

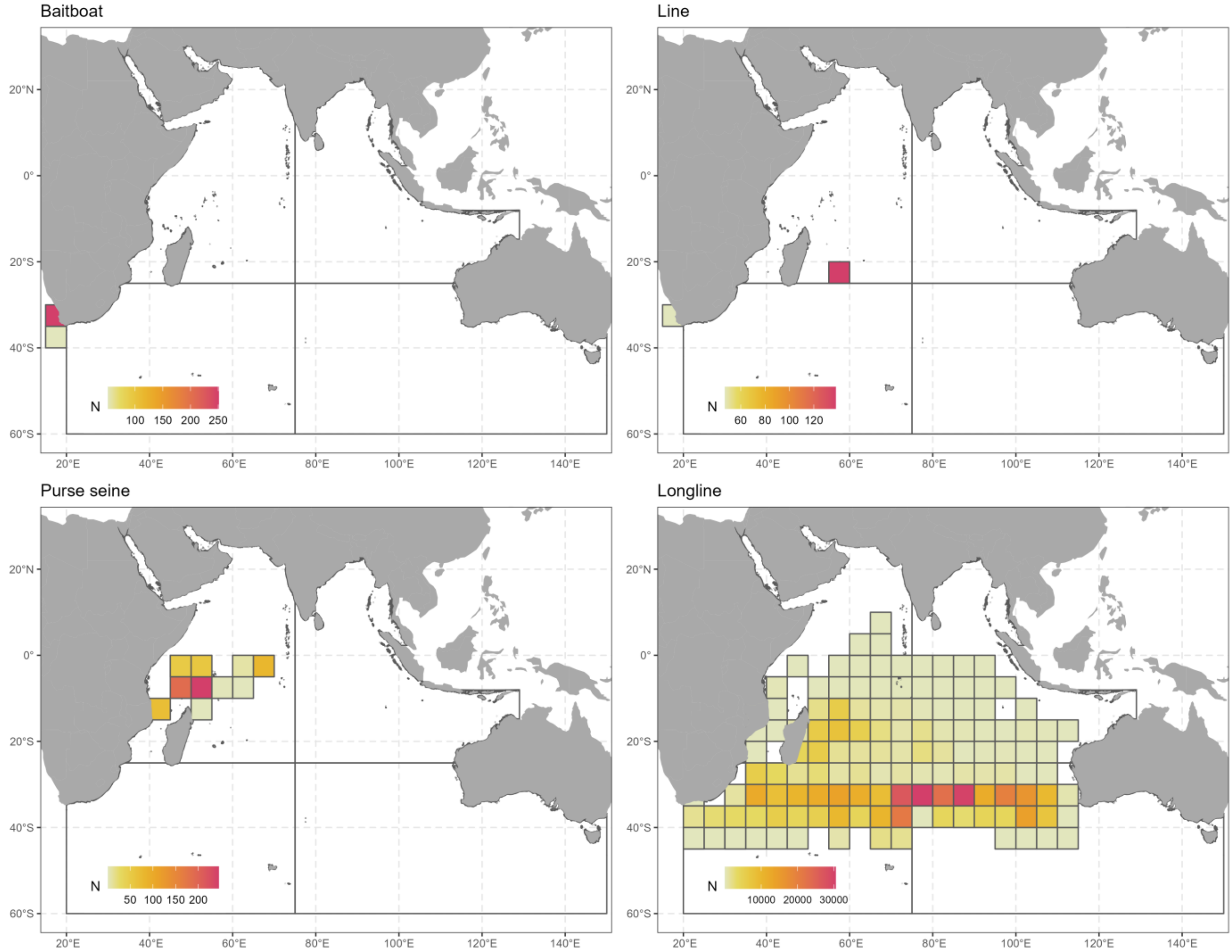

Figure 1: Spatial distribution of albacore tunas sampled for morphometrics (n = 481,564)

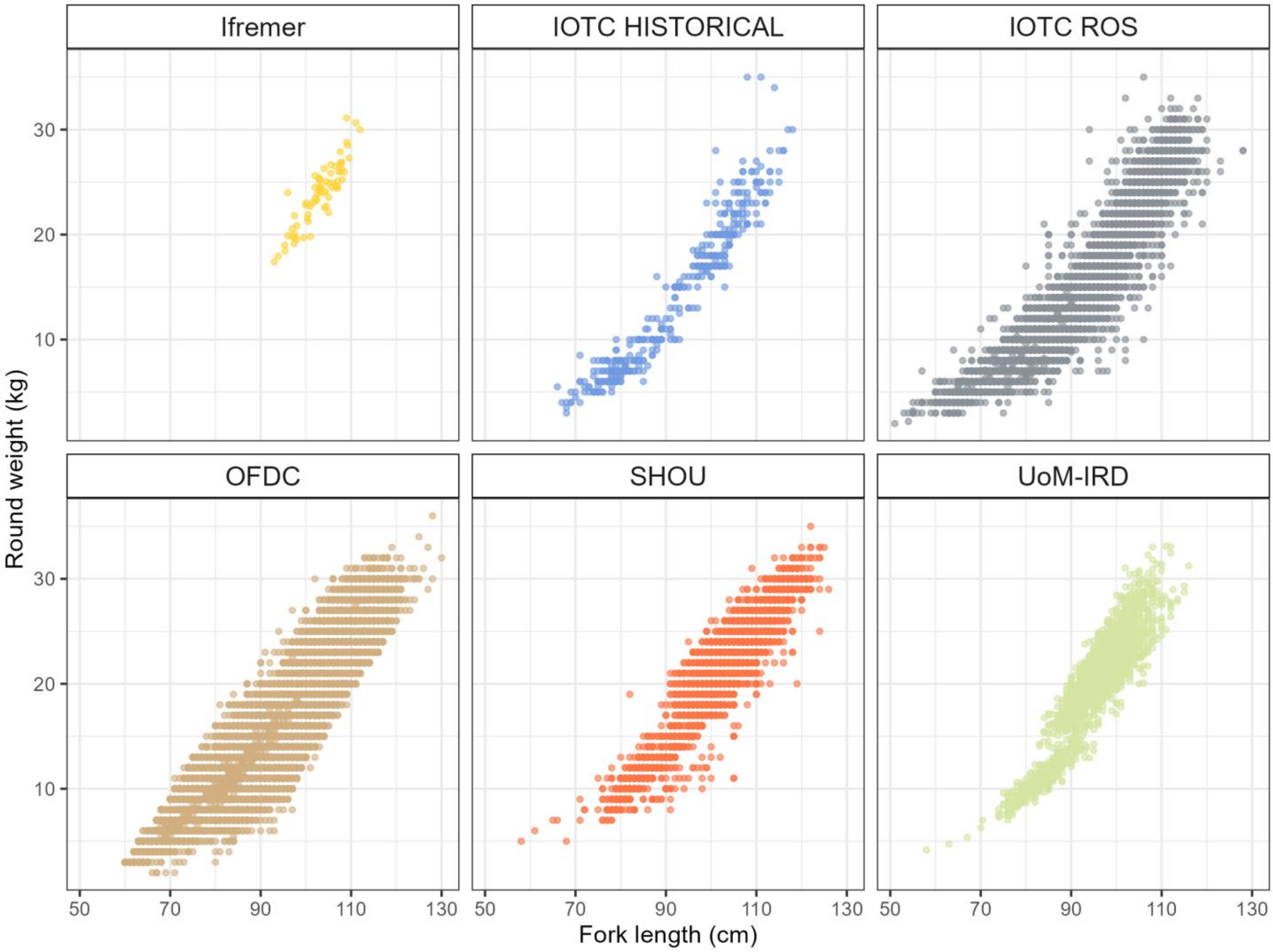

Figure 2: Relationship between fork length (cm) and round weight (kg) for albacore by data source available for the study. ROS = Regional Observer Scheme; OFDC = Overseas Fisheries Development Council; SHOU = Shanghai Ocean University; UoM = University of Mauritius; IRD = Institut de Recherche pour le Développement

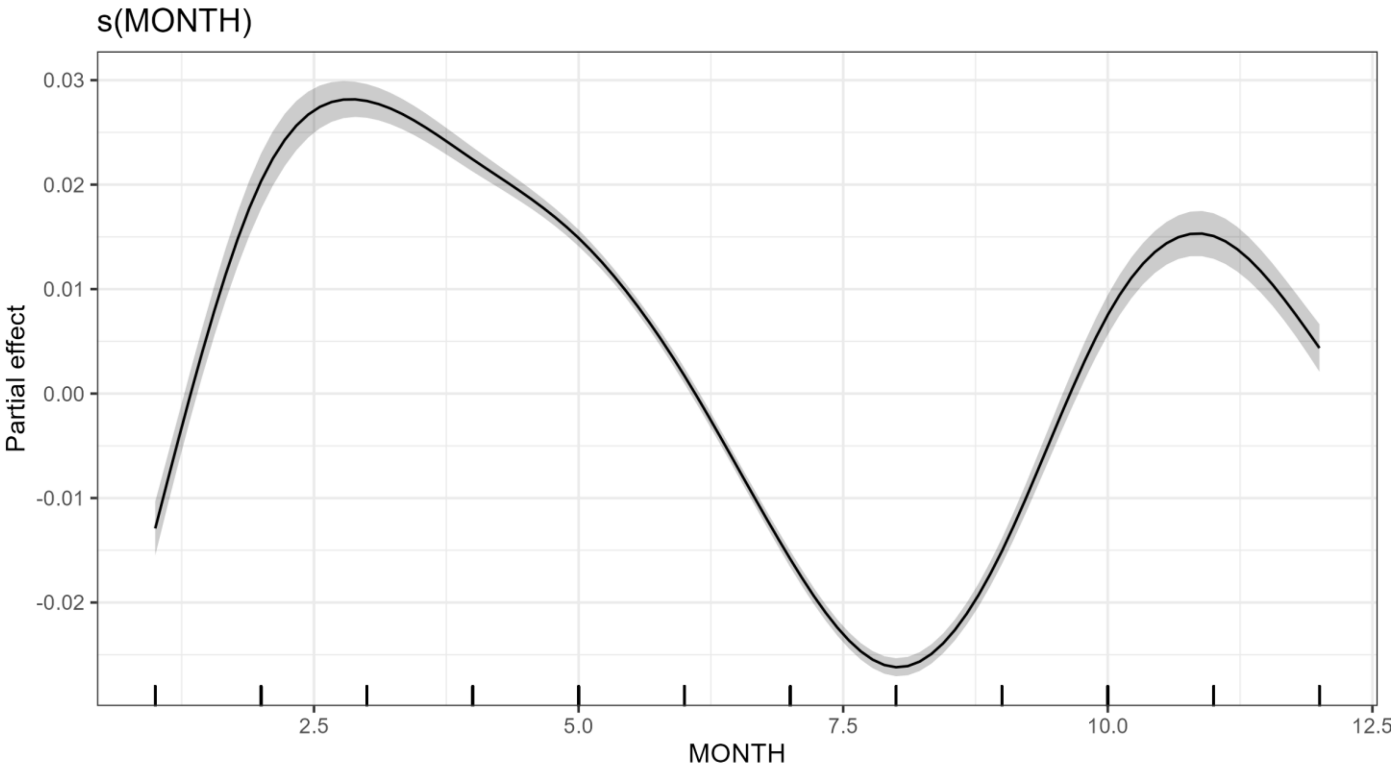

Figure 3: Partial effect of month on log10 values of round weight of Indian Ocean albacore

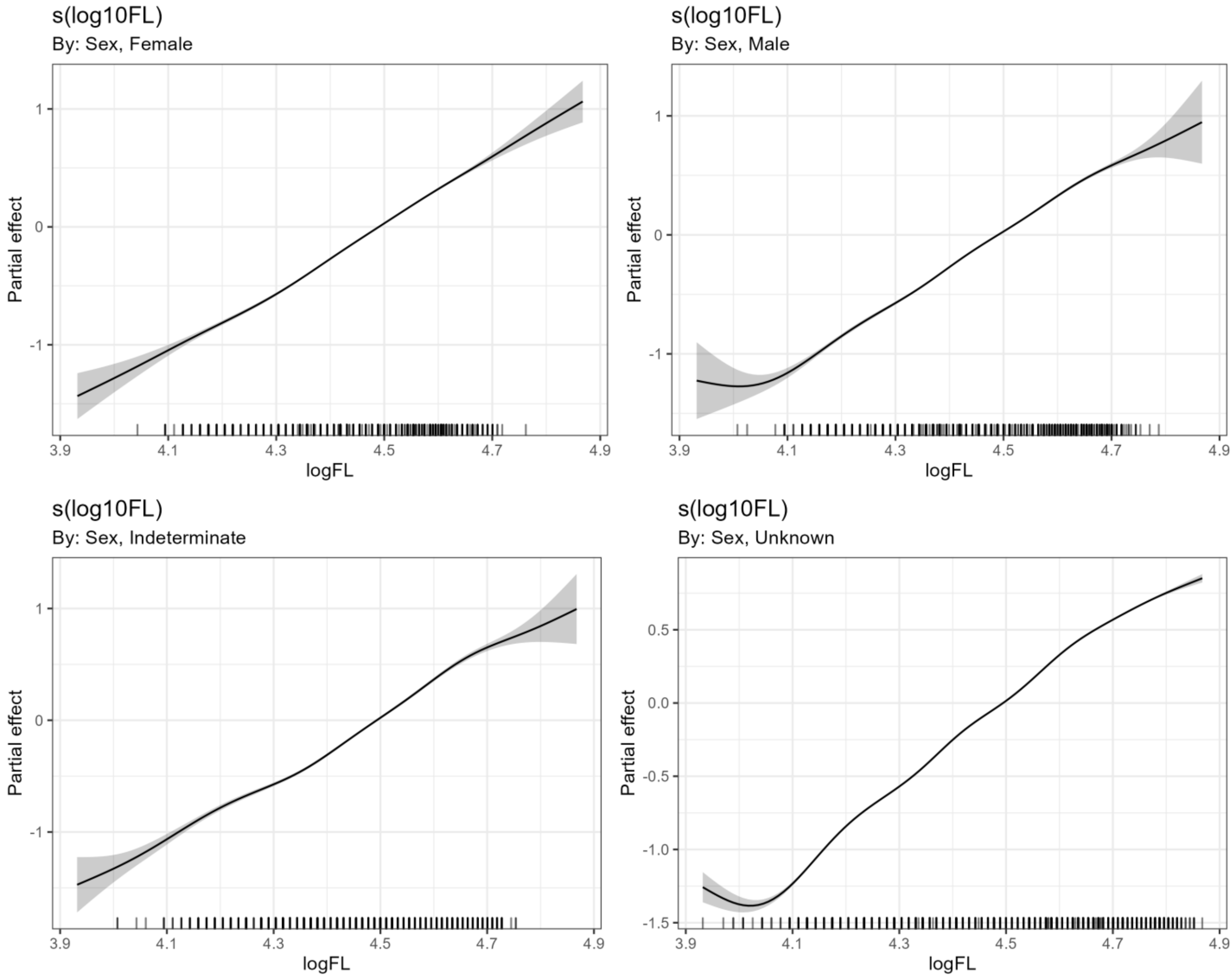

Figure 4: Partial effect of fork length by sex on log10 values of round weight of Indian Ocean albacore

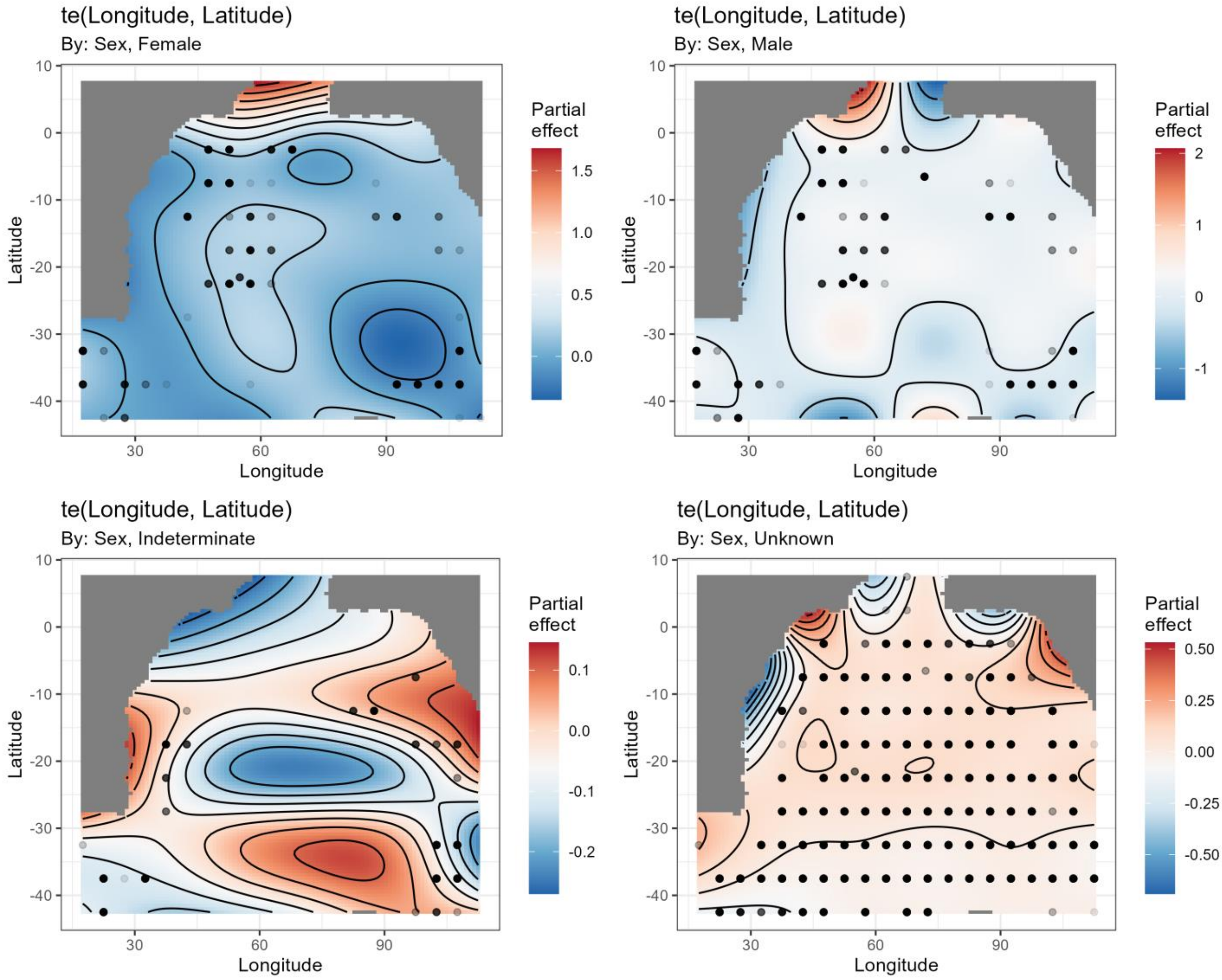

Figure 5: Partial effect of longitude and latitude by sex on log10 values of round weight of Indian Ocean albacore

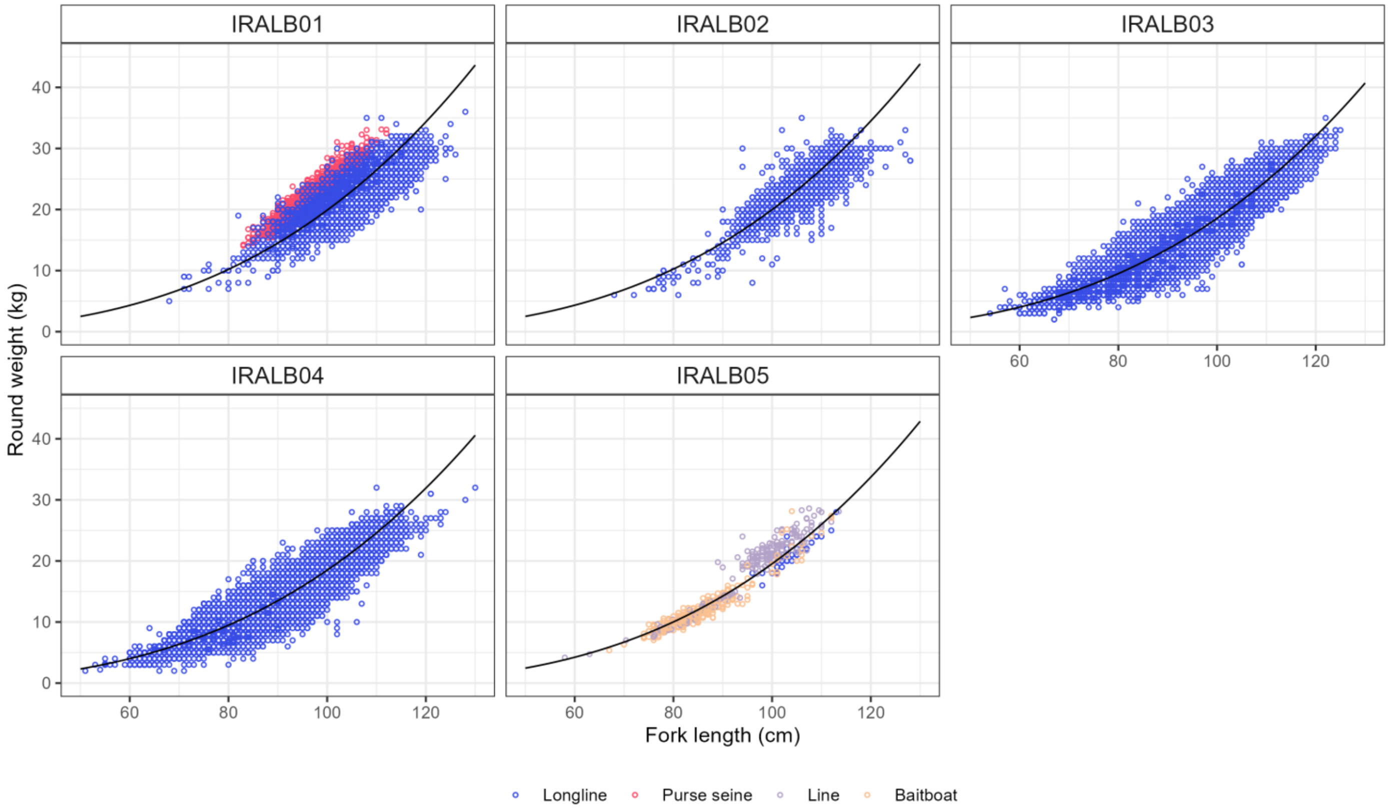

Figure 6: Relationships between fork length (cm) and round weight (kg) for Indian Ocean albacore estimated by large areas used for the analysis of the catch per unit effort. The black solid line corresponds to the mean regression fitted to the log-transformed data

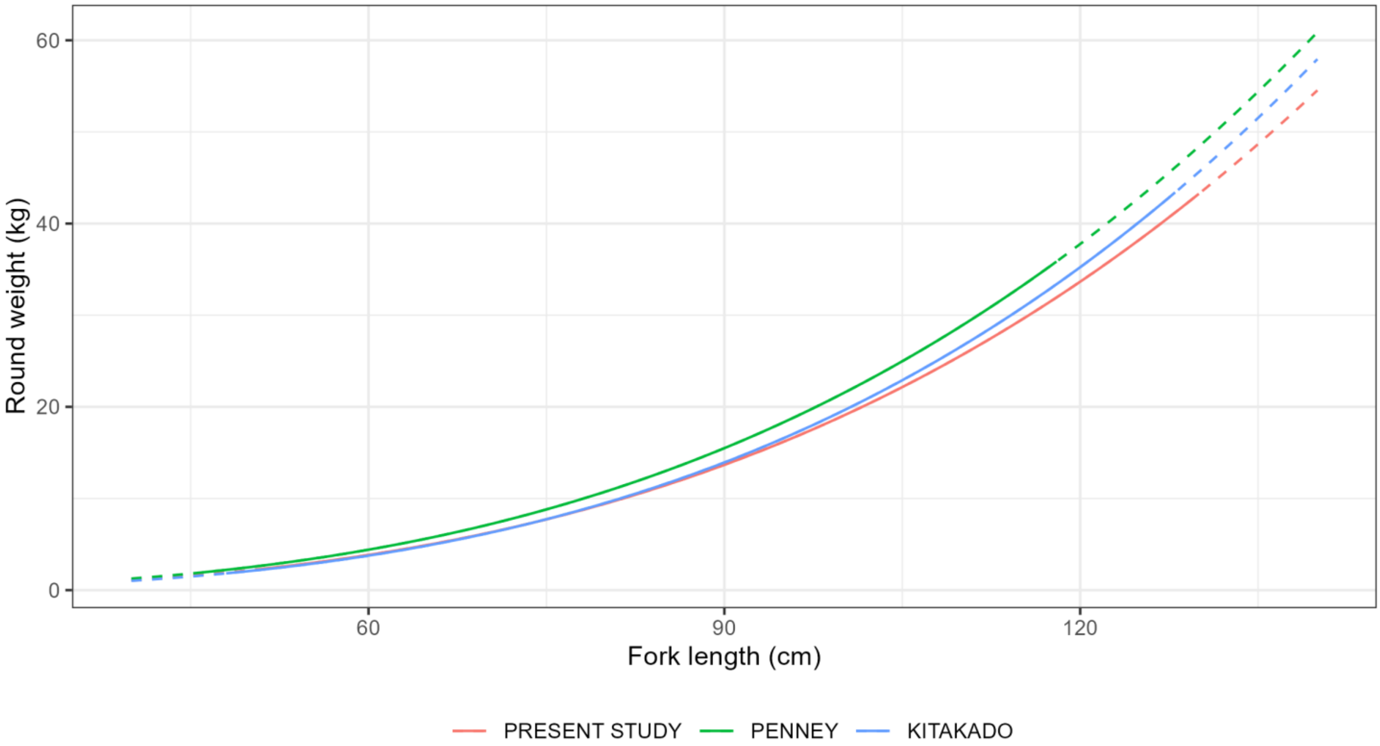

Figure 7: Comparison of the relationships between fork length (cm) and round weight (kg) fitted to the overall data set considered in the present study (red solid line; n = 481,564; fork length range = 51-130 cm) with the relationship used in the stock assessment model in 2019 (green solid line; n = 1,008; fork length range = 46-118 cm) (Penney 1994) and 2022 (blue solid line; n = 8,862; fork length range = 48-128 cm) (Kitakado et al. 2019). Solid lines represent models predictions for the ranges of fork lengths observed in the original data sets when dashed lines represent predictions outside the range of the independent variable data

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Appendix: Models diagnostics

Generalized Additive Models

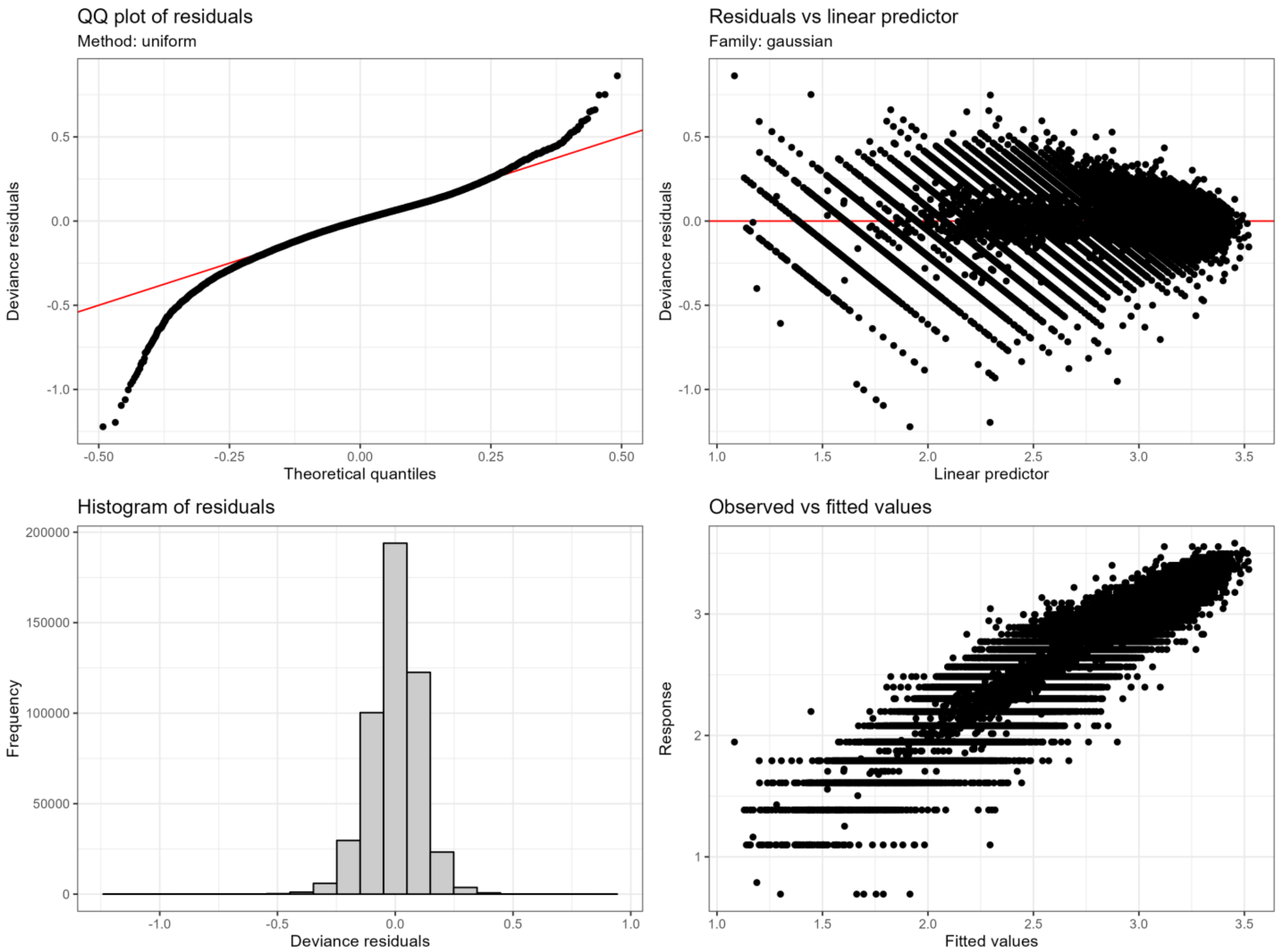

Figure 8: Diagnostic of the best selected generalized additive model of round weights (Eq. 5) of Indian Ocean albacore as selected from the lowest AIC

Linear models

Best selected model with all covariates except fishery

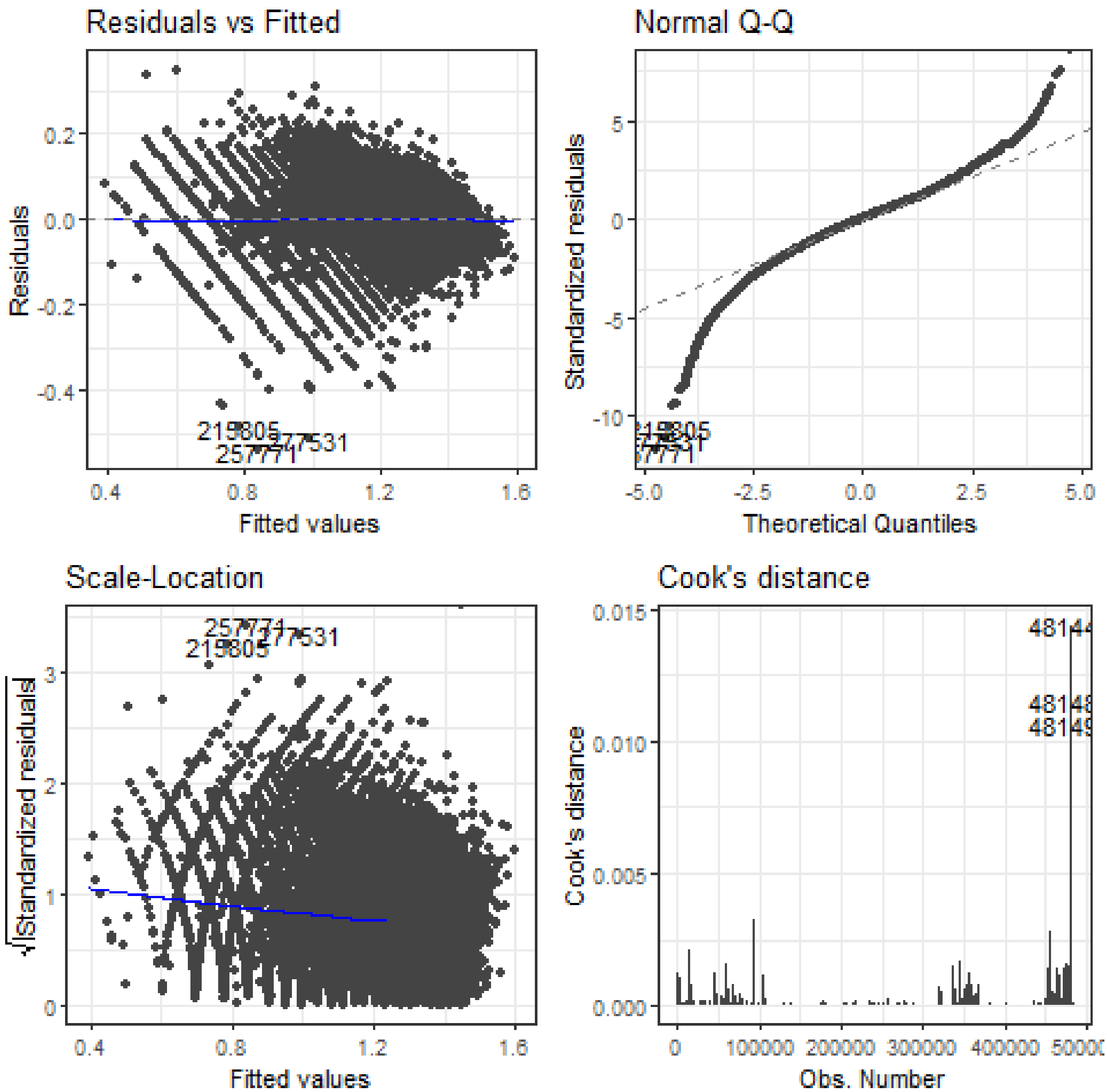

Figure 9: Diagnostic of the best selected linear regression model of round weights including all covariates (Eq. 6) except fishery as selected from the lowest AIC

Model with fork length and area

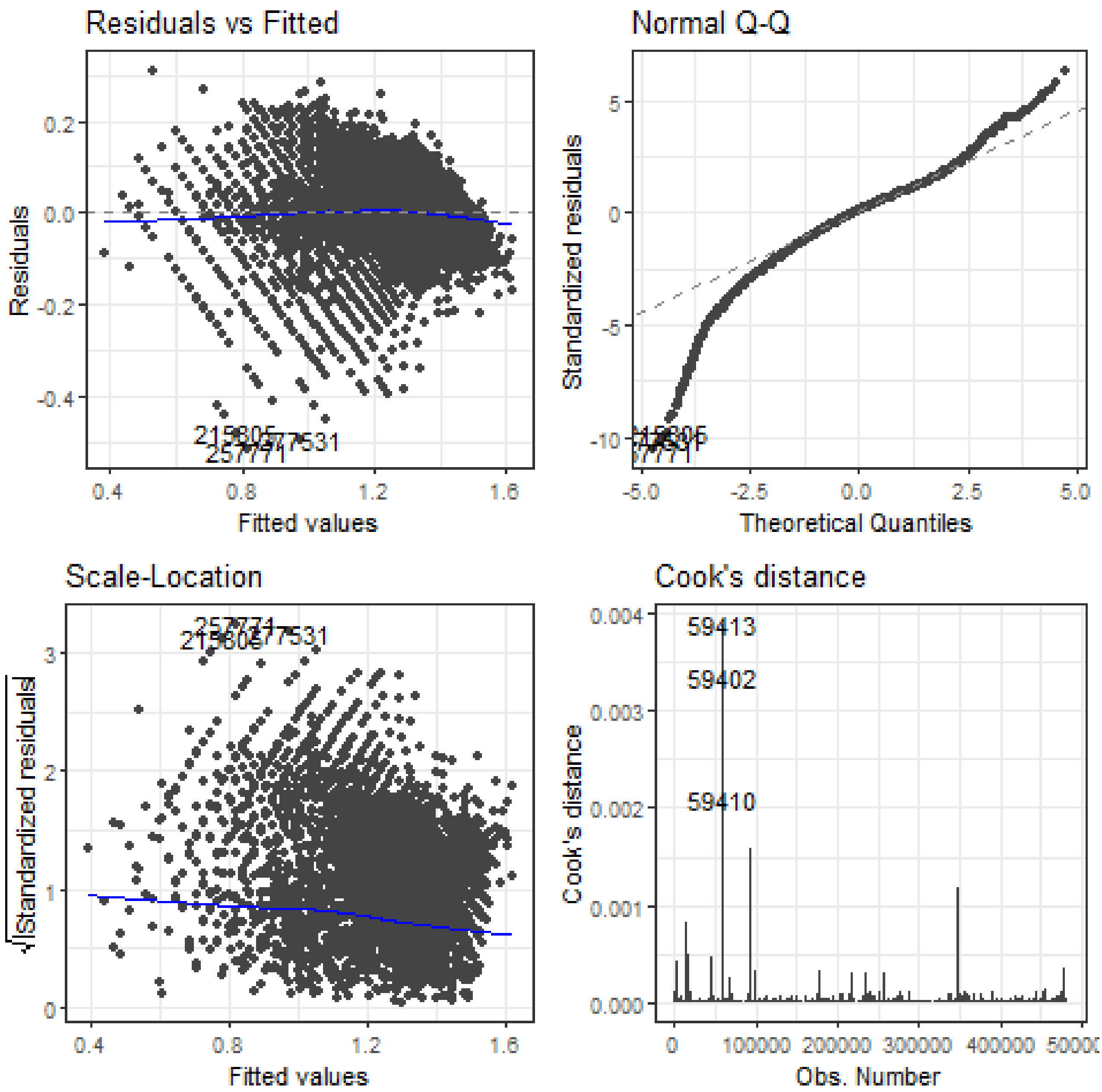

Figure 10: Diagnostic of the linear regression model of round weights of Indian Ocean albacore including only fork length (log10 transformed) and area as covariates

Model with fork length

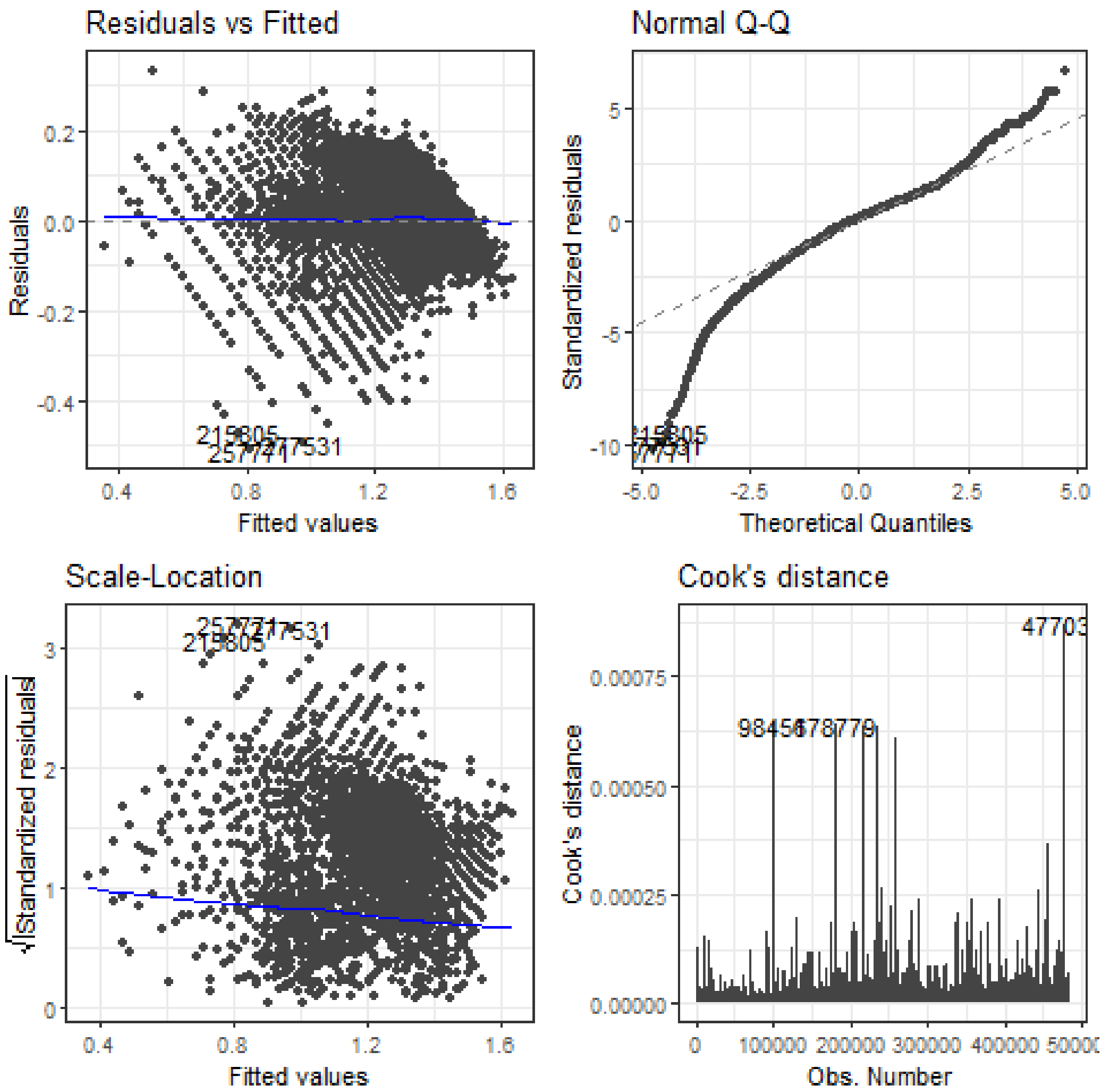

Figure 11: Diagnostic of the linear regression model of round weights of Indian Ocean albacore only including fork length (log10 transformed) as covariate