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Growth heterogeneity of Bigeye tuna *Thunnus obesus* in the Indian Ocean explored by the mixed effect model

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Abstract

The life history traits including growth, is the fundamental and key process of population dynamics and stock assessment, which gains much attention in recent years. Based on the data collected by Chinese observers onboard from 2013 to 2018, the growth of Bigeye tuna was analyzed, with the spatial-temporal variations. A total of 8,806 individuals were measured, with fork length ranging from 51 to 203 cm and the gilled & gutted & tailed weight from 2.5 to 138.0 kg. The predicted power length-weight function indicated that the estimate of condition factor *a* is 1.26 $\times10^{-5}$ with spatial-temporal ranges 1.20~1.37$\times10^{-5}$, while the estimate of allometric growth parameter *b* is 3.05. Mixed effect models were established to estimate the variations from different years, quarters and regions, while 7 model candidates were considered with different random effects sources. AIC and Root Mean Square Error values revealed that the mixed effect model with all variations performed best. Results from the best model indicated that 1) there is no substantial different for Bigeye tuna in the north or south Indian Ocean divided by 15°S; 2) individuals collected in the quarter 1&2 tended to gain more weight than those collected in quarter 3&4 at the same length; and 3) individuals collected in 2015 and 2016 grew with better condition, while those in 2014 and 2017 gained much less weight at the same length. The outcome from this study could profit the stock assessment and fisheries management for this important tuna species in the Indian Ocean, and the methodology used in this paper can also be applied to the heterogeneity study for other species in both coast water and far ocean.

Keywords： Distant-Water Fisheries; Trophic Tuna; Length-Weight Relationship; Mixed effect model; Spatial-Temporal Variations

Introduction

Bigeye tuna, is one of the most important tropical tuna, in the Indian Ocean fishery. IOTC WPTT conducts stock assessment for bigeye tuna every three years to provide management advice for this important fishery. The growth characteristics are essential information during the stock assessment.

During the estimation of catches at size for bigeye tuna in IOTC, the equation used to convert from length into weight in longline fishery is that gilled and gutted weight(kg) = 1.59 $\times 10^{-5} \times$Fork length(cm)$^{3.04}$. This equation was summarized from multilateral catch monitoring Benoa conducted in 2002~2004, whose sample size is 12,047, with fork length ranging from 70 to 187cm.

In this study, this equation was updated based on the observer data from China longline fishery in the western Indian Ocean from 2013 to 2018, with 8,806 samples and fork length ranging from 51 to 203 cm. Moreover, the spatial and temporal variations were also explored by mixed effects model.

Materials and Methods

Biological information used in this study is sourced from the records by observers aboard Chinese longline vessels from 2013 to 2018.The vessels operated in the west of Indian Ocean targeting bigeye tuna (Figure. 1). This study used the upper-jaw fork length (cm), gilled & gutted & tailed weight (kg), time and location to evaluate the growth characteristics and spatial-temporal viability. Most of 8,806 samples were collected in the tropical waters of northern Indian Ocean in 2017 and 2018, with the large number of samples in the first quarter and the fourth quarter (Table 1).

In this study, weight-at-length relationship was used to describe the growth characteristics of bigeye tuna in the Indian Ocean. A power law weight-at-length model (Keys 1928) with log-normal error was used:

$$(1) \quad W = aL^b e^{\varepsilon} \qquad \varepsilon \in N(0, {\sigma_w}^2)$$

where W is the wet weight of an individual fish (kg), L is the body length (cm), a is the condition factor, and b is the allometric growth parameter. In this study, the weight-length model was log-transformed.

$$(2) \quad ln(W) = ln(a) + b\ln(L) + \varepsilon \qquad \varepsilon \in N(0, {\sigma_w}^2)$$

Generalized Linear Model (M1) was applied to fit the general weight-at-length relationship of bigeye tuna, while Mixed effect models were another approach used in this study to quantify the spatial-temporal heterogeneity of growth. Based on previous studies, especially CPUE standardization and stock assessment, the temporal intervals were chosen by yearly to quarterly (Hoyle et al. 2016; Langley 2016). Based on the distribution of bigeye tuna and fisheries, the study area was divided the Indian Ocean into the north region and the south region with a boundary of 15°S, while the northern region was divided into the east and west with a boundary of 80°E (Hoyle et al. 2016; Langley 2016). Since Chinese longline fleets seldom operates in the eastern Indian Ocean (figure 1), only the individuals in the western Indian Ocean are studied.

Mixed effect model includes fixed effect and random effect. Fixed effect is used to reflect the average condition of the growth, while random effect is used to analyze the heterogeneity caused by different data sources. The random effects from year (2013-2018), quarter (four quarters) and region (the north and the south) were applied to the intercept parameters the condition factor a:

$$(3) \quad ln(W) = \ln(a) + b\,ln(L) + \varepsilon = (FE + RE) + b\,ln\,(L) + \varepsilon$$

where FE is the fixed effects, RE is the random effects, L is the body length (cm).

All the combinations of random effects were implemented, leading to total seven candidate models. The mixed effect models (M2-M8, table 2) considered random effects from Quarter (M2, $RE=RE_q$), Year (M3, $RE=RE_y$), Region (M4, $RE=RE_r$), Quarter + Year (M5, $RE=RE_q+RE_y$), Quarter + Region (M6, $RE=RE_q+RE_r$), Year + Region (M7, $RE= RE_y+RE_r$), and Quarter + Year + Region (M8, $RE=RE_s+RE_y+RE_r$), respectively.

The performance of these candidate models was measured by the Akaike information criterion (AIC) and Root Mean Squared Error (RMSE), which have been widely used to compare the quality of models (Akaike 1974; Burnham et al. 2002). Lower AIC and RMSE values indicate a better model. All these modelling processes and analyses were conducted, using packages lme4 and nlme the R (version: R i386 3.3.1) (Bates et al. 2015; Pinheiro et al. 2018).

Results and Discussions

The size ranges from 51 to 203 cm with the average of 137 cm, and the dominant size class is 100~170 cm. The weight ranges from 2.5 to 138.0 kg with the average of 45.0 kg, and the dominant weight falls in the range of 10~80 kg. The length and weight range of samples in 2016 are wider than those from 2013 to 2015 (Figures 2 and 3).

Based on generalized linear model (M1), the estimated mean of ln(a) in weight-at-length relationship was -11.45 with the 95% confidence interval from -11.52 to -11.38. The estimate of condition factor a was 1.07 (0.99, 1.14) $\times 10^{-5}$. The estimated allometric growth parameter b was 3.08 (3.07, 3.10) (Figure 4). The general growth characteristic of bigeye tuna was given by the Fixed effect, which was described as $W=1.26\times 10^{-5} L^{3.05}$, indicating that the size of bigeye tuna was fusiform and the growth pattern was uniform.

The means of AIC and RMSE for all 7 mixed effect models were significantly less than that of M1. M8 which was taken into account the quarter, year and region, had the best fitting with the smallest mean value of AIC and RMSE (Table 2). The results indicated that there were significant spatial-temporal variations in the weight-at-length relationship (Figures 5-7).

Although the introduction of spatial variable *Region* can improve the deviance explained of the model, there was little difference in the weight-at-length relationship of bigeye tuna in the southern and northern regions of the Indian Ocean (Figure. 5). In the case of the same length, bigeye tuna is larger in the first and second quarters, while the weight increased slightly in the third and fourth quarters (Figure. 6). Individuals collected in 2015 and 2016 were heavier at the same length, and the difference was more obvious in the large individuals (Figure. 7).

Since the data in this paper are from longline catch, the weight used is GT (kg) and the length used is the upper fork length (cm). This is different from the data collected by other literatures. For example, the values of *a* and *b* in total weight-at-total length relationship of bigeye tuna in Fishbase are 0.01318 and 3.02, respectively. The values of *b* are basically consistent, but the values of *a* are greatly different. Firstly, the processing weight without gills, tails and gut can remove the impact of gonadal development and short-term drastic changes in food intake on body weight, while the use of the upper fork length instead of total length can reduce the measurement error caused by measuring the damaged caudal fin. However, it will also make it difficult to compare with observations from other studies.

The current stock assessment considers both the temporal and spatial structures. Since this research covers sufficient sample size and time periods, we suggest the results could provide knowledge and be used in the stock assessment process for Bigeye tuna, especially the temporal (quarter's) variations of growth. Also, the methodology used in this paper can also be applied to the heterogeneity study for other species in both coast water and far ocean.

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Tables

Table 1 The sample size of biological data for Bigeye tuna in the Indian Ocean from 2013 to 2018

Year	Quarter 1	Quarter 2	Quarter 3		Quarter 4		Total
	North	North	North	South	North	South	
2013	-	-	-	-	622	-	622
2014	288		5	25	-	-	318
2015	-	-	-	-	164	-	164
2016	235	-	-	-	1478	48	1761
2017	601	378	358	64	1316	599	3316
2018	27	257	447	322	1458	114	2625

Table 2 The constructions, AIC and root mean squared error (RMSE) of the alternative models for length-weight relationships of Bigeye tuna in the Indian Ocean

Model	Random effects	AIC	RMSE
M1	None	-11194	0.611
M2	Quarter	-11504	0.588
M3	Year	-12061	0.575
M4	Region	-11313	0.611
M5	Quarter+Year	**-12365**	0.571
M6	Quarter+Region	-11551	0.585
M7	Year+Region	-12092	0.573
M8	Quarter+Year+Region	**-12365**	**0.568**

Table 3 The spatial and temporal variations of *a* estimates in the length-weight relationships for Bigeye tuna in the Indian Ocean

Variations	random effects	ln$a$	a ($\times 10^{-5}$)
North	0.00334	-11.28	1.26
South	-0.00334	-11.29	1.26
Quarter 1	0.042859	-11.24	1.32
Quarter 2	0.019195	-11.26	1.28
Quarter 3	-0.03812	-11.32	1.21
Quarter 4	-0.02393	-11.31	1.23
2013	-0.0093	-11.29	1.25
2014	-0.05052	-11.33	1.20
2015	0.084914	-11.20	1.37
2016	0.05424	-11.23	1.33
2017	-0.04559	-11.33	1.20
2018	-0.03376	-11.32	1.22

Figures

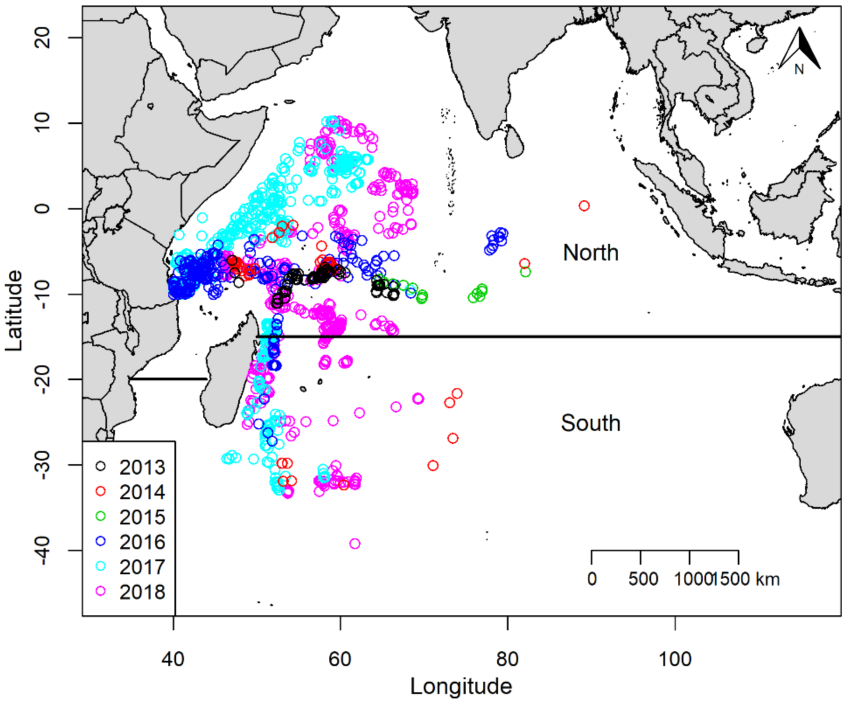

Figure 1 The sampling positions of Bigeye tuna in the Indian Ocean from 2013 to 2018

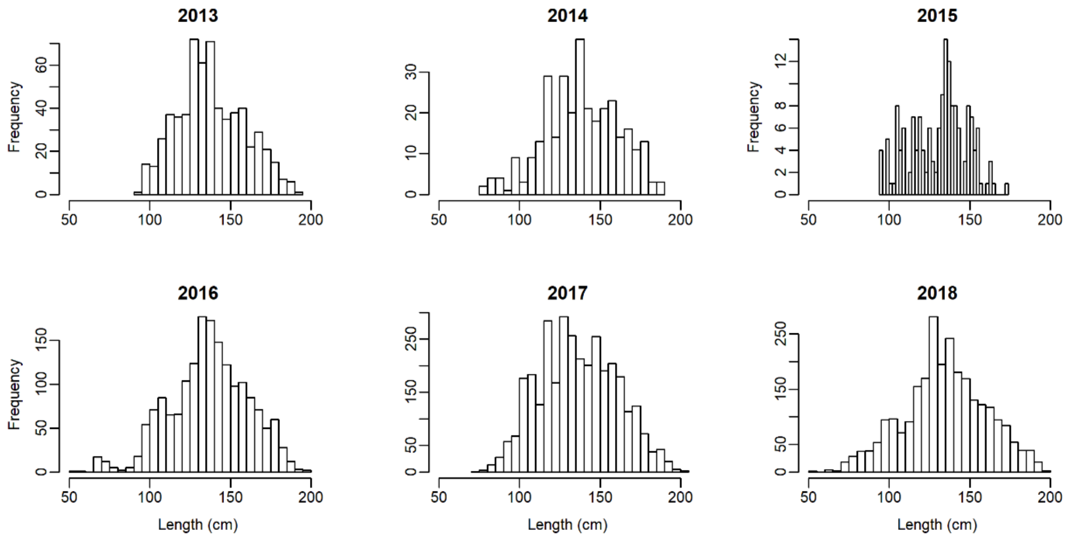

Figure 2 The length variations among 2013~2018 of Bigeye tuna in the Indian Ocean

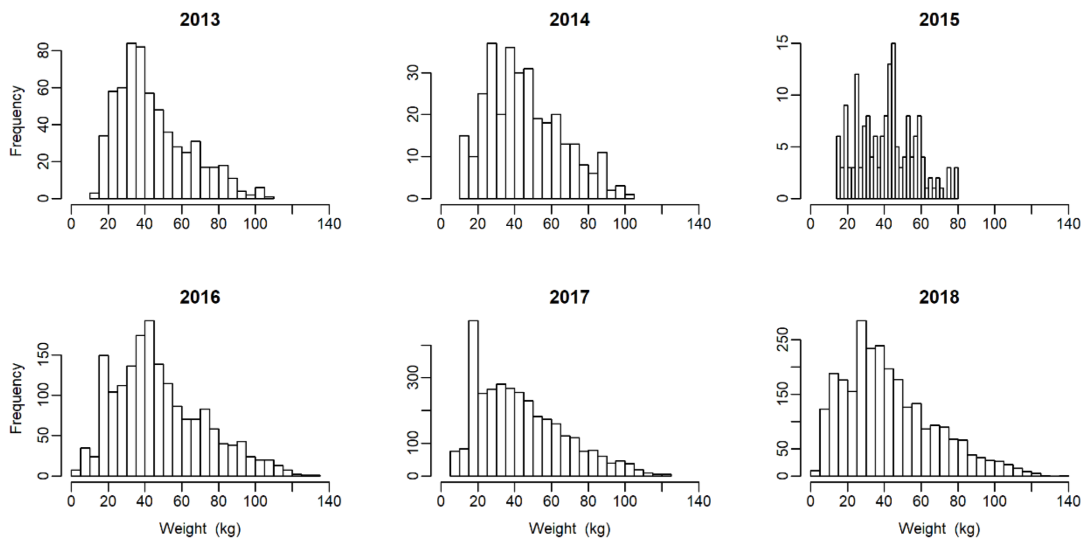

Figure 3 The weight variations among 2013~2018 of Bigeye tuna in the Indian Ocean

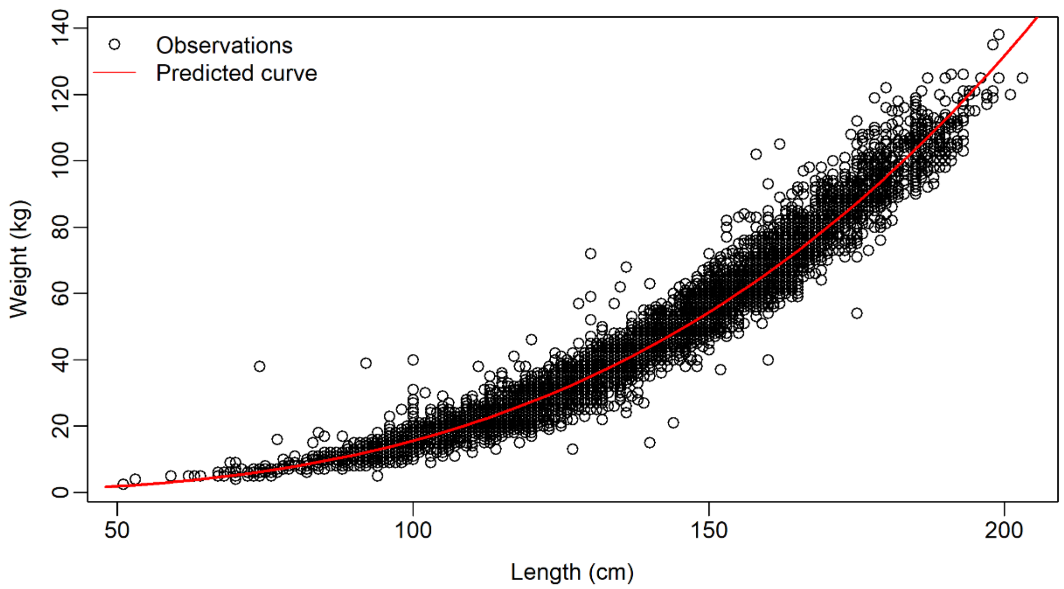

Figure 4 The observations and predicted curve from the generalized linear model for length-weight relationships of Bigeye tuna in the Indian Ocean

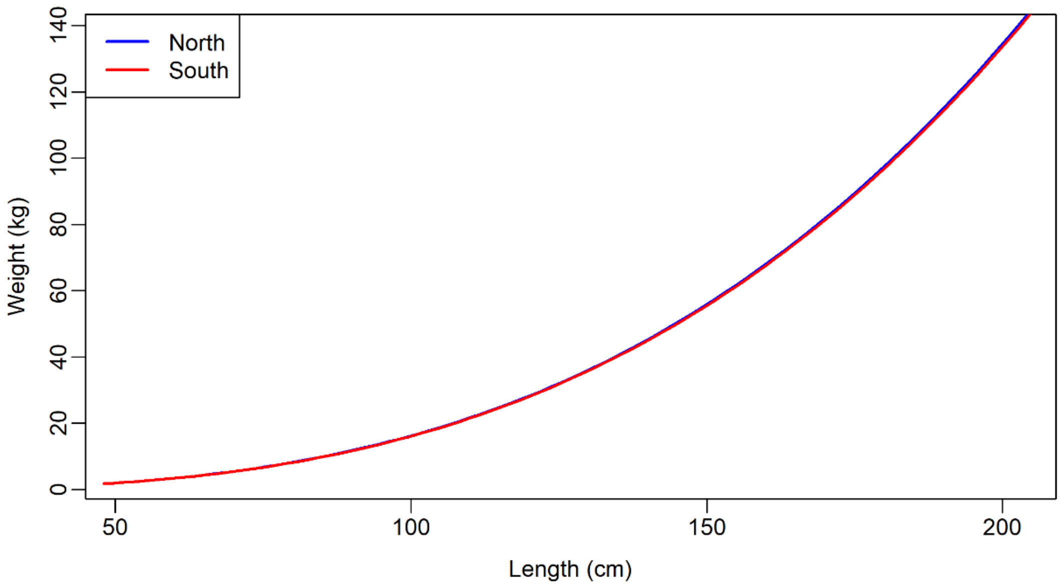

Figure 5 The spatial variations of length-weight relationships for Bigeye tuna in the Indian Ocean

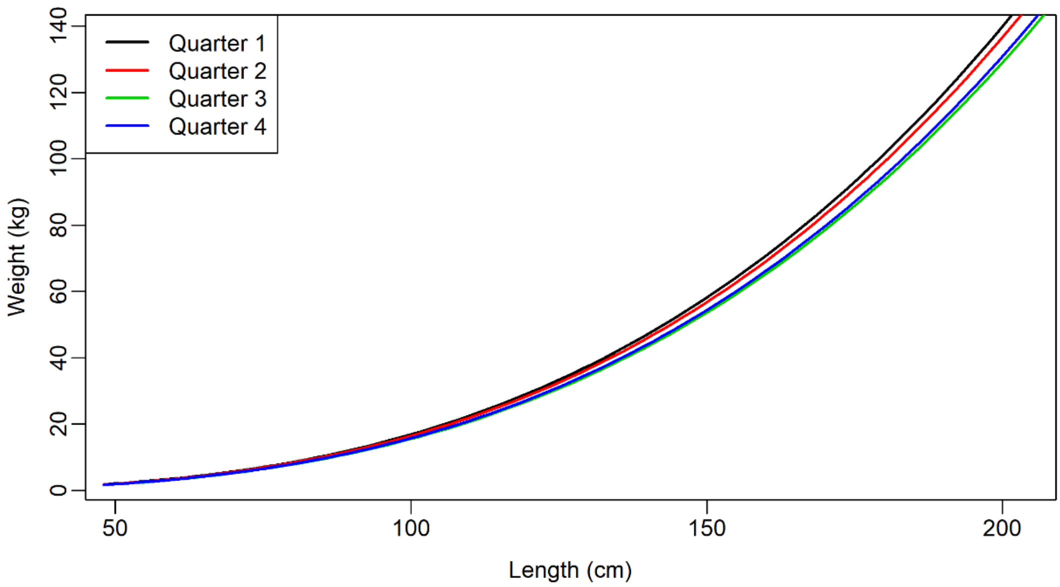

Figure 6 The variations in different quarters of length-weight relationships for Bigeye tuna in the Indian Ocean

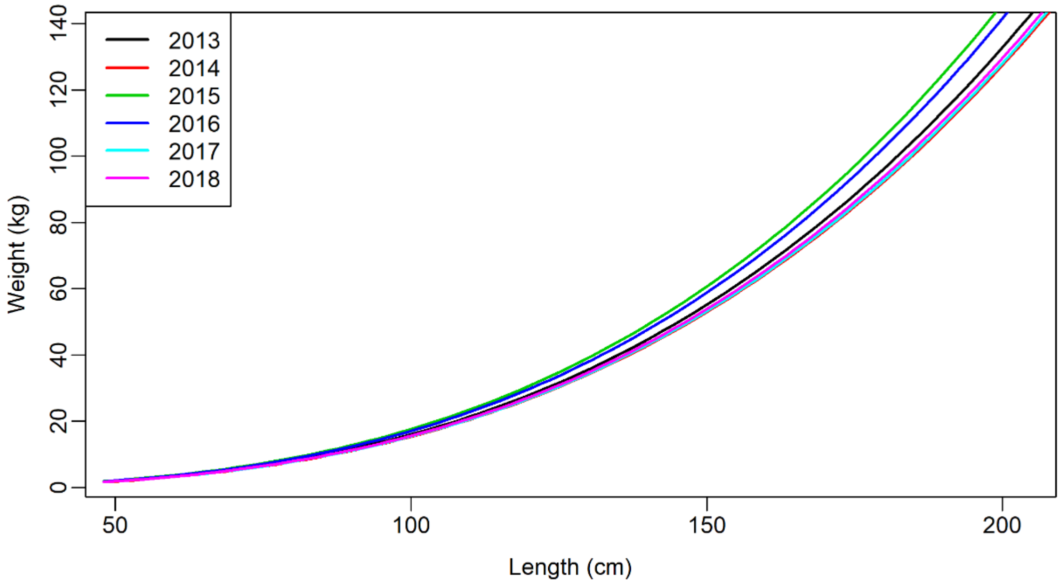

Figure 7 The variations in different years of length-weight relationships for Bigeye tuna in the Indian Ocean