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Catch per unit effort, condition factor and length-weight relationship of albacore tuna (*Thunnus alalunga)*, yellowfin tuna (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*) in the longline tuna fishery in the eastern Pacific Ocean

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ABSTRACT

Highly migratory tuna species play an important economic role and ecosystem function worldwide. They are mainly caught in tropical and subtropical areas of the Pacific, Atlantic and Indian oceans. Data collected by the Chinese longline fishery in the high seas of the Eastern Pacific Ocean from 2014 to 2015 were analysed to estimate the catch per unit effort (CPUE), length and weight frequency, length-weight relationship, relative condition factor and Fulton's condition factor for albacore tuna (*Thunnus alalunga*), yellowfin tuna (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*). The results showed that this fishing technique was highly selective for these three species. Albacore tuna represented the major portion of the catches at 76.17%. Yellowfin and bigeye tuna represented 8.24 and 11.68% of the total of specimens, respectively. The remaining 3.9% were bycatch such as *Katsuwonus pelamis, Acanthocybium solandri, Ruvettus pretiosus, Xiphias gladius*, *Lampris guttatus, Carcharodon carcharias* and *Scomberomorus guttatus*. The average fork length for albacore tuna was 90-100 cm; yellowfin tuna, 100-130 cm and bigeye tuna, 125-165 cm. The average weight for albacore tuna was 15-20 kg; yellowfin tuna, 20-50 kg and bigeye tuna, 35-55 kg. The CPUE (based on fish per one thousand hooks) for albacore, yellowfin tuna and bigeye tuna ranged from 1.6 to 9.82, 1.07 to 2.66 and 1.06 to 3.45, respectively. The parameters of the length-weight relationship showed a negative allometric growth regression of 2.7135 for albacore tuna, 2.3275 for yellowfin tuna and 2.4047 for bigeye tuna. Nevertheless, the albacore and yellowfin tuna females were characterised by positive allometry (b>3). The analyses also showed that the relative condition factors (K_{rel}) of the three fish species were greater than one, implying that they were in good physiological condition, good water quality and healthy organisms.

Keywords: China, Fishing effort, Fish per hook, Tuna

Introduction

Tuna fishes belonging to the Scombridae family comprises more than a dozen species (Yuta, 2018). The most commercially important species in the eastern Pacific Ocean are the albacore tuna (*Thunnus alalunga*), yellowfin tuna (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus)* (Zhu *et al*., 2008). The main albacore tuna fisheries are in temperate and tropical waters. Asian longliners overexploit this species and the catch volume is estimated at 68,000 t. However, the biomass of the stock is not affected by the industry (Goni *et al*., 2009; Cosgrove *et al*., 2014, 2015; Froese and Pauly, 2017). With respect to yellowfin tuna, the size of fish caught varied from 40 to 170 cm TL (1.2 and 100 kg) (Collete *et al*., 2011). The spawning biomass has increased in recent years and the level of fishing mortality in the Eastern Pacific Ocean is slightly below the maximum sustainable yield (MSY) of approximately 13% (586 400 t) (Froese and Pauly, 2017). Bigeye tuna can grow up to 250 cm (98 inches) or 8 feet in length. The maximum weight of individuals may exceed 180 kg, the all-tackle angling record is 178 kg (Grewe and Hampton, 1998). The stock exploited in 2015 was 78,000 t. The species is fully exploited with spawning stock biomass and fishing mortality at MSY (Froese and Pauly, 2017).

The albacore, yellowfin and bigeye tuna are also the principal species of tunas in the trade (Majkowski, 2007). However, the longline tuna fishery in the eastern Pacific has limited regulations which may impact the tuna population and bycatch which needs to be resolved by research on the fishery's sustainability (ICCAT, 2017). Our analysis aims to understand and characterise the biological distribution, tuna species catches and distribution of longline fishers in the eastern Pacific. Our results would lay the foundations for developing appropriate management strategies to minimise bycatch and maximise economic performance.

The length-weight relationship (LWR) and Fulton's condition factor (K) are the two major parameters used in fishery research and are closely related (Froese, 2006). These parameters are essential and focus on various important biological aspects, such as the general well-being of fish, appearance of first maturity and onset of spawning, which can be assessed using the condition factors derived from LWR with K (Le Cren, 1951; Pepin, 1995; Shaofei *et al*., 2015). Our investigation also includes the conversion of growth-in-length equations to growth-in-weight (for use in stock assessment models), estimating the biomass from length data, calculating the total weight of fish caught using length-frequency data, determining the relative condition factor of small fish compared to large fish and comparing the regional life histories of certain fish species (Pitcher and Hart, 1982; Petrakis and Stergiou, 1995; Goncalves *et al*., 1997; Binohlan *et al*.,1998; Zhenhua and Gang, 2016). Although LWR and K reflect the growing conditions of some fish, previous research has not combined these analyses. As a result, consistent trends reflecting the characteristics of albacore, yellowfin and bigeye tuna populations in the eastern Pacific Ocean require further study.

The present study aimed to analyse the developing tuna longline fishery targeting albacore, yellowfin and bigeye tuna in the eastern Pacific Ocean using data collected by Chinese longlines. The species selectivity, catch per unit effort (CPUE), length and weight frequency, LWR and Fulton's condition factor (K) were investigated. This information will assist in managing the rapidly developing tuna longline fishery in the eastern Pacific Ocean.

Materials and methods

Survey information

This study was conducted within the east Pacific high seas east of Tahiti Island, French Polynesia (14°S; 115°W and 23°S; 124°W) (Fig. 1). The longline survey was conducted during the albacore, yellowfin and bigeye tuna season between January 2014 and December 2015. The survey was completed onboard the commercial tuna longliner "Xin shi ji 71" which is 56.5 m long, 8.5 m wide and 3.65 m deep, with a gross tonnage of 634 and main engine power of 735 kW. The fishing location is provided in Fig. 1. Catch and effort data was collected during the fishing season by surveying the daily operation results. A total of 873 specimens were measured. The variables observed during the study were: total fork length (Lt) (to the nearest centimetre), total weight (Wt) (to the nearest kilogram), the total number of fish caught per day and sex of the fish.

Fishing effort and catch per unit effort (CPUE)

The fishing equipment used in the commercial tuna longliner "Xin shi ji 71" was constructed with nylon monofilament with a diameter of 5.4 mm with polyester branch lines of 4 mm diameter attached through swivels. The length of the main rope between the two lines was 33 m, containing 26 branching lines in each branch. During the survey, there was a total of 58 fishing operations (days), representing a fishing effort slightly above 3770 hooks per day. In this study, the time series of fishing effort and species CPUE were used to identify patterns in daily and seasonal variability. The fishing effort (f) and CPUE can be calculated with the following equations, modified from De Metrio and Megalofonou (1988):

$$F = \left(\frac{N_h}{1000} x f_d\right) \qquad (1)$$

$$CPUE_i = \frac{C_i}{f} \qquad (2)$$

where N_h is the number of hooks on the longline per day, f_d is the number of fishing days per fishing operation and C_i is the number of fish caught.

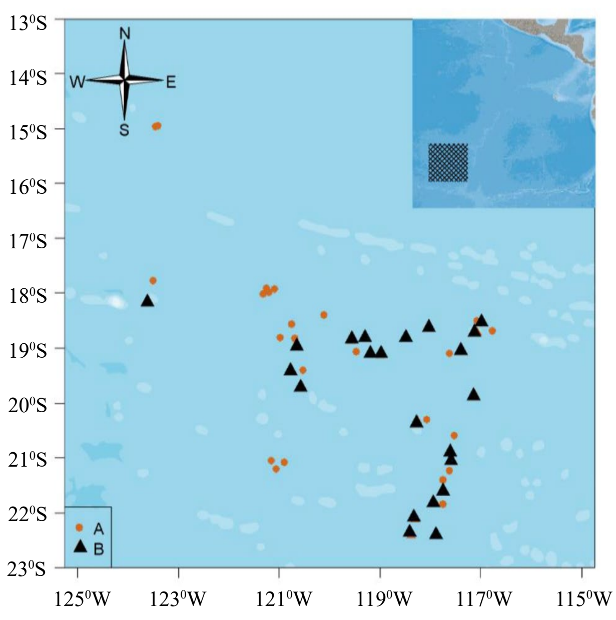

Fig. 1. Distribution of deployment locations in the survey of the tuna longline fishery (A: filled circle indicate counter-retrieval-operations and B: filled triangle indicate forward retrieval operations; the plot in the upper right corner represents the distance from the shoreline of the survey area (shaded in grey)

Fork length and weight frequency

The fork length frequency was calculated using a 10 cm fork length interval between: 80 and 130 cm for albacore tuna, 85 and 150 cm for yellowfin tuna and 75 and 180 cm for bigeye tuna (creating a total of 5, 8 and 10 interval classes in the frequency distributions of albacore, yellowfin and bigeye tuna, respectively). The left boundary was closed in each interval. For example, for the interval of 80-90 cm, the fork length was from 80 cm (>80 cm) to 90 cm (90 cm).

Weight frequency was calculated using a 5 kg weight interval that was between 10 and 35 kg for albacore tuna. The weight interval for yellowfin and bigeye tuna was calculated with a 10 kg weight interval from 10 to 80 kg and then a 5 kg interval for the size of 80 to 110 kg. A total of 5, 6 and 10 intervals for weight frequency distributions were determined for albacore, yellowfin and bigeye tuna, respectively.

Length-weight relationship

The LWRs were estimated using Eq. 3 (Froese, 2006):

$$W_t = aLb_t \quad (3)$$

where W_t is the whole-body weight (kg), L_t is the total fork length (cm), *a* is the power function coefficient (the regression intercept) and *b* is the allometric coefficient (the regression slope).

The value of b varies from 2 to 4 but is generally close to 3 (N'da *et al*., 2006 a and b). The value of b determines the type of growth: *b*=3 shows the growth is isometric and so the specific density of the fish does not change: *b*< shows the growth is negative allometric and therefore, the fish length increases faster than it grows; *b*>3 shows positive allometry and therefore, the fish grows faster than the increase in its length (Anderson and Neumann, 1996).

Since the LWR (3) is nonlinear, the coefficients *a* and *b* cannot be obtained directly and therefore, require further transformation into a linear equation by using natural logarithms on both sides:

$$\ln W_t = \ln a + b \ln L_t \quad (4)$$

Fulton's condition factor and relative condition factor

For each individual, the relative condition factor (K_{rel}) and Fulton's condition factor (K) were calculated using the following equations (Le Cren, 1951; Megalofonou, 1990; Froese, 2006; Macías *et al*., 2012):

$$K_{rel} = \frac{W_t}{aL^b_t} \quad (5)$$

$$K = \frac{W_t}{L^3_t} \times 100 \quad (6)$$

Results and discussion

Species composition

The species composition was estimated as the percentage of occurrence of each species. Albacore represented the highest percentage of all species caught (76.17%); yellowfin 8.25% and bigeye tuna 11.68% of the total catch. Skipjack tuna (*Katsuwonus pelamis),* wahoo (*Acanthocybium solandri)* and oilfish (*Ruvettus pretiosus)* represented 2.75% of the total catch. All other bycatch species (*Xiphias gladius*, *Lampris guttatus, Carcharodon carcharias* and *Scomberomorus guttatus*) contributed 1.15% of the total catch (Table 1). These results indicate that the tuna longline used in the eastern Pacific to catch albacore, yellowfin tuna and bigeye tuna was highly selective for these species (Zhu *et al*., 2008). Mohamed and Eldin (2012) and this study attribute the presence of bycatch species in tuna longlines to the season, gear design and fishing operation.

Fishing effort, daily catch and CPUE

Fig. 2 shows the daily catch and catch per unit effort (CPUE) of albacore, yellowfin tuna and bigeye tuna based on 58 fishing days during the fishing season. The average fishing effort was approximately 3.77 effort units per day (3770 hooks per day). The daily catch of albacore ranged from 6 to 37 fish per day with an average of 13±4 fish per day and between 105 and 647.5 kg per day (Fig. 2a). The daily catch of yellowfin tuna ranged from 4 to 10 fish per day with an average of 5±2 fish per day and from 140 to 350 kg per day with an average of 175±70 kg per day (Fig. 2b). The catch of bigeye tuna ranged from 4 to 13 fish per day and between 180 and 585 kg per day (Fig. 2c). Although albacore catches occurred throughout the 58 fishing days, the CPUE varied from 1.6 to 9.82 and showed significant daily differences. It displayed a unimodal temporal distribution that peaked on 26 November 2015. This result relates to the transition period (between autumn and winter fishing effort) when the distribution of effort was scattered. The lowest CPUE was recorded on 28 October and 26 December, 2015 (Fig. 2a). Furthermore, previous studies by Vayghan *et al*. (2020) in the southern Atlantic Ocean, Rochman *et al*. (2017) in the eastern Indian Ocean and Hoyle *et al*. (2012) in the south Pacific Ocean, suggest that the CPUE of albacore tuna in the present study are comparable to the catches in other oceans. The CPUE for albacore tuna in the Southern Atlantic Ocean during the period of 2009 to 2015 was 7.44 to 41.53 fish per 1000 hooks (Vayghan *et al*., 2020). In the eastern Indian Ocean during the

Table 1. Species composition of the high seas pelagic longline tuna fishery in the eastern Pacific Ocean

Species	Common name	Number of fish caught	% of total catch
Thunnus alalunga	Albacore tuna	665	76.17
Thunnus obesus	Bigeye tuna	102	11.68
Thunnus albacares	Yellowfin tuna	72	8.25
Katsuwonus pelamis	Skipjack tuna	7	0.80
Lampris guttatus	Opah	2	0.23
Acanthocybium solandri	Wahoo	12	1.37
Carcharodon carcharias	Shark	3	0.34
Scomberomorus guttatus	Seerfish	2	0.23
Xiphias gladius	Swordfish	3	0.34
Ruvettus pretiosus	Oilfish	5	0.57

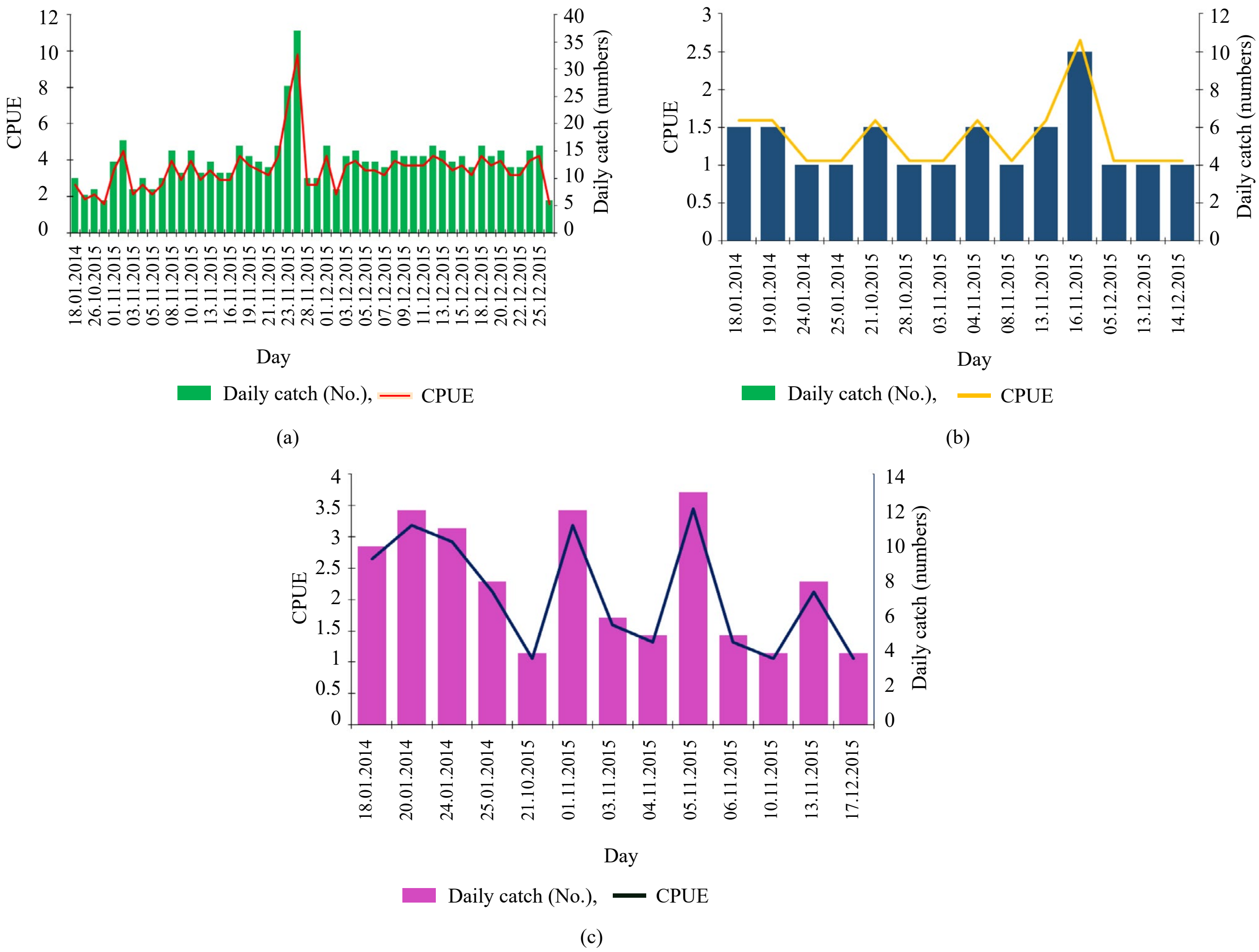

Fig. 2. Catch per unit effort (CPUE) and daily fish catch in numbers a: Albacore tuna; b: Yellowfin tuna and c: Bigeye tuna

period of 2006 to 2015, the CPUE was from 0.117 to 0.519 fish per 100 hooks (Rochman *et al*., 2017). In the south Pacific Ocean during the period of 1960 to 2011, the CPUE was from 0.15 to 4 fish per 100 hooks (Hoyle *et al*., 2012). For yellowfin tuna catches, the CPUE varied from 1.07 to 2.66. The unimodal temporal distribution was evaluated on 16 November 2015 and was found to be related to the transition between autumn and winter fishing efforts. The lowest CPUE was observed between 24 and 25 January 2014; 28 October to 03 November 2015 and 05 to 14 December 2015 (Fig. 2b). The CPUE of yellowfin tuna caught in the Indian Ocean during 1977-2017 and in the western and central Pacific Ocean during 1960-2014 as reported by Lee *et al*. (2018) and Davies *et al*. (2014) were similar to those obtained in the present study. Unlike the previous two species, bigeye tuna showed clear seasonality in its catch with three principal peaks: the first during winter season on 20 January 2014 (with a CPUE of 3.18 per unit effort), the second in autumn on 01 November 2015 (with a CPUE of 3.18 per unit effort) and the third one on 05 November 2015 (with a CPUE of 3.45 per unit effort), these peaks related to the beginning of the transition between the autumn and winter fishing effort. The lowest CPUE was recorded on 21 October (autumn fishing effort), 10 November (transition period between autumn and winter fishing effort) and 17 December (winter fishing effort) 2015 (Fig. 2c). Similar to the other two species, the CPUE results of bigeye tuna were also comparable to those reported for the western and central Pacific Ocean during the period 1960-2014 (Davies *et al*., 2011; Harley *et al*., 2014). Caution should be taken as the CPUE obtained for albacore, yellowfin and bigeye tuna in this study may not reflect the actual abundance of these species in the fishing area. This is due to the temporal trends in CPUE being strongly influenced by various factors associated with fishing practices and environmental conditions (Sadiyah *et al*., 2012; Abad-Uribarren *et al*., 2018; Vayghan *et al*., 2020). The results obtained in this study are also consistent with the conclusions of Song *et al*. (2013; 2014) with a similar fishing period and fishing season. For example, both studies focused on the target population in a natural period with overlaps in the range of hook distribution due to the vertical movement of the day, night and weather conditions, resulting in variations in CPUE.

Fork length and weight frequency

The fork length frequency distribution of albacore, yellowfin and bigeye tuna fork lengths is depicted in Fig. 3. The size of albacore tuna ranged from 80 to 130 cm and the fork length of 90 to 100 cm were the dominant class of the albacore tuna catches (Fig. 3a). This fork length range represents approximately 69 and 50.8% of the albacore males and females, respectively. On an average, the proportion of fish with a fork length above 93 cm and below 98 cm represented 75% of the albacore males in this fork length range. Additionally, the proportion of fish with a fork length above 98 cm represented 65% of the albacore females (Fig. 3a). The least number of individuals were categorised in the fork length group of 110 to 120 cm and from 120 to 130 cm. For yellowfin tuna, fork length ranged from 80 to 160 cm and most individuals were seen in the 110 to 130 cm category, representing approximately 31.6 and 70% of the total caught specimens of males and females, respectively. The least number of individuals possessed fork lengths of 140 to 160 cm, representing 10.3% of the total specimens (Fig. 3b). Finally, for bigeye tuna, the fork length ranged from 75 to 180 cm and 125 to 155 cm category dominated the catch, representing approximately 47% of the total specimens caught. However, the individual females with fork lengths ranging from 135 to 165 cm were dominant, representing approximately 46.15% of the total female specimens, while the fork length range of 105 to 145 cm was the most dominant for the male specimens, representing approximately 66% (Fig. 3c). The length data for the three tuna species was higher than that obtained by Zhu *et al*. (2008) in the eastern Pacific Ocean, whose fork lengths varied from 70 to 118 cm, 93 to 170 cm and 60 to 202 cm for albacore, yellowfin and bigeye tuna, respectively. The length range of the three tuna species in this study was in agreement with the results obtained by Hoyle *et al*. (2012) on albacore in the south Pacific Ocean. Our results were contrary to that of Harley *et al*. (2014) on bigeye tuna in the western and central Pacific Ocean.

The weight frequency distributions of the three tuna species are shown in Fig. 3. The minimum and maximum weight size ranges of the different species were: albacore tuna - 10-35 kg, yellowfin tuna - 10-80 kg and bigeye tuna - 5-110 kg. For albacore tuna, the dominant weight range was from 15 to 20 kg, representing 55.96% of the total specimens. This weight range represented approximately 61.64 and 50.61% of the albacore males and females, respectively (Fig. 3a). The class with the least specimens ranged from 30 to 35 kg and represented 3.61 and 6.79% of males and females, respectively. The dominant weight range for yellowfin tuna was from 20 to 50 kg and represented 72.41% of the total specimens. This weight range represented 70.03% of the total female specimens and 73.68% of the total male specimens. The maximum weight of the males ranged from 50 to 60 kg and maximum weight of the females ranged from 60 to 80 kg (Fig. 3b). Finally, for bigeye tuna, the weight range from 35 to 55 kg was the dominant class, representing 46.88% of the total specimens. This weight range represented 33.33% of female specimens and 66.67% of male specimens. The maximum weight of the males was 108 kg, while that of the female was 85 kg, therefore, on average, bigeye males weighed more than females.

Length-weight relationship

Table 2 shows the regression equations of the relationship between fork length (cm) and total weight (kg) of albacore, yellowfin and bigeye tuna caught in this study. In general, the allometric coefficients (*b*) of the females were significantly greater than those of the males for all three species ($p<0.05$). The allometric coefficients of the three species were lower than 3, excluding those of albacore and yellowfin tuna females, which were greater than 3. The b-coefficients of albacore and yellowfin tuna

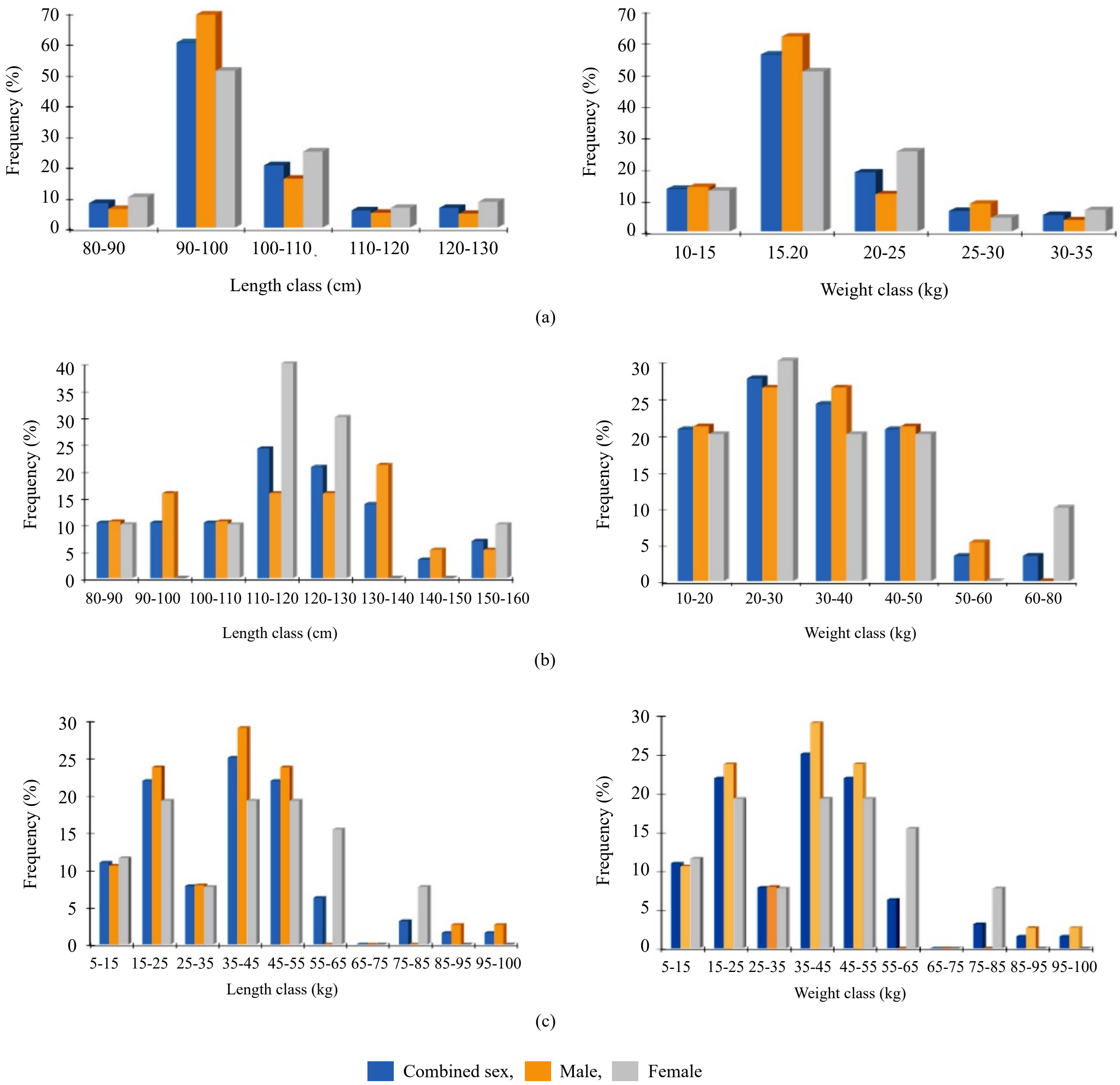

Fig. 3. Length (left) and weight (right) frequency distributions of (a) Albacore tuna, (b) Yellowfin tuna and (c) Bigeye tuna

Table 2. Length-weight relationship of albacore, yellowfin and bigeye tuna

Species	Parameters	'a'	R^2	'b'
Albacore tuna	Combined sex	$y = 7E\text{-}05x^{2.7135}$	0.7494	Negative
	Males	$y = 8E\text{-}05x^{2.6845}$	0.7584	Negative
	Females	$y = 5E\text{-}06x^{3.2956}$	0.7784	Positive
Yellowfin tuna	Combined sex	$y = 0.0001x^{2.577}$	0.8329	Negative
	Males	$y = 0.0005x^{2.3263}$	0.8143	Negative
	Females	$y = 7E\text{-}06x^{3.208}$	0.9096	Positive
Bigeye tuna	Combined sex	$y = 0.0002x^{2.494}$	0.8886	Negative
	Males	$y = 0.0002x^{2.494}$	0.8848	Negative
	Females	$y = 0.0002x^{2.5079}$	0.9111	Negative

males, as well as that of bigeye tuna, revealed that they all had negative allometric growth relationships, which means that the length of these species increased faster than their growth. Conversely, the albacore and yellowfin tuna females had positive allometric growth relationships, which meant that the growth of these species was faster than the increase in their lengths. In addition, the combined sex allometric coefficients of these species were less than 3, which indicated that the length and growth of these species increased rapidly with age. There was a good fit of data to the regression (R^2) as the values of albacore, yellowfin tuna and bigeye tuna were high (Table 2). These results were similar to those obtained by Mohamed and Eldin (2012) and Zhenhua and Yu (2016). The albacore and yellowfin tuna females were characterised by positive allometry, which is similar to the results of Zhu *et al*. (2008) in the eastern Pacific Ocean and Hoyle *et al*. (2012) in the South Pacific Ocean for the yellowfin tuna and albacore tuna, respectively. The LWR of fish species is affected by certain factors, such as season, habitat, food availability, feeding rate, gonad development, sex, spawning period, health, conservation techniques and location (Froese, 2006; Zhu *et al*., 2008).

Distribution of Fulton's condition factor and relative condition factor

The average condition factor (*K*) for the three species was 1.92±0.15, 1.41±0.18 and 1.74±0.42 for albacore, yellowfin and bigeye tuna, respectively. In addition, the average relative condition factor (K_{rel}) was 1.01±0.08, 1.34±0.31 and 1.02±0.2 for these three species, respectively (Table 3). However, the value of *K* was greater than one for all species, which meant that our specimens were in good condition. When the sexes were combined, the *K* values decreased as the fork length range increased (Fig. 4). The *K* value was greater when the fork length range was 80-90 and 85-95 cm for all the 3 species. For albacore tuna, the *K* values of both the females and males were similar, with the difference less than 1% in the fork length range of 80-100 cm. In contrast, when the fork length ranged from 110 to 130 cm, the female *K* values were significantly greater than those of the male *K* values. For yellowfin tuna, the *K* values of the males were greater than those of females for all fork length ranges except for the fork length range of 120-130 cm, where they were equal. For bigeye tuna, the

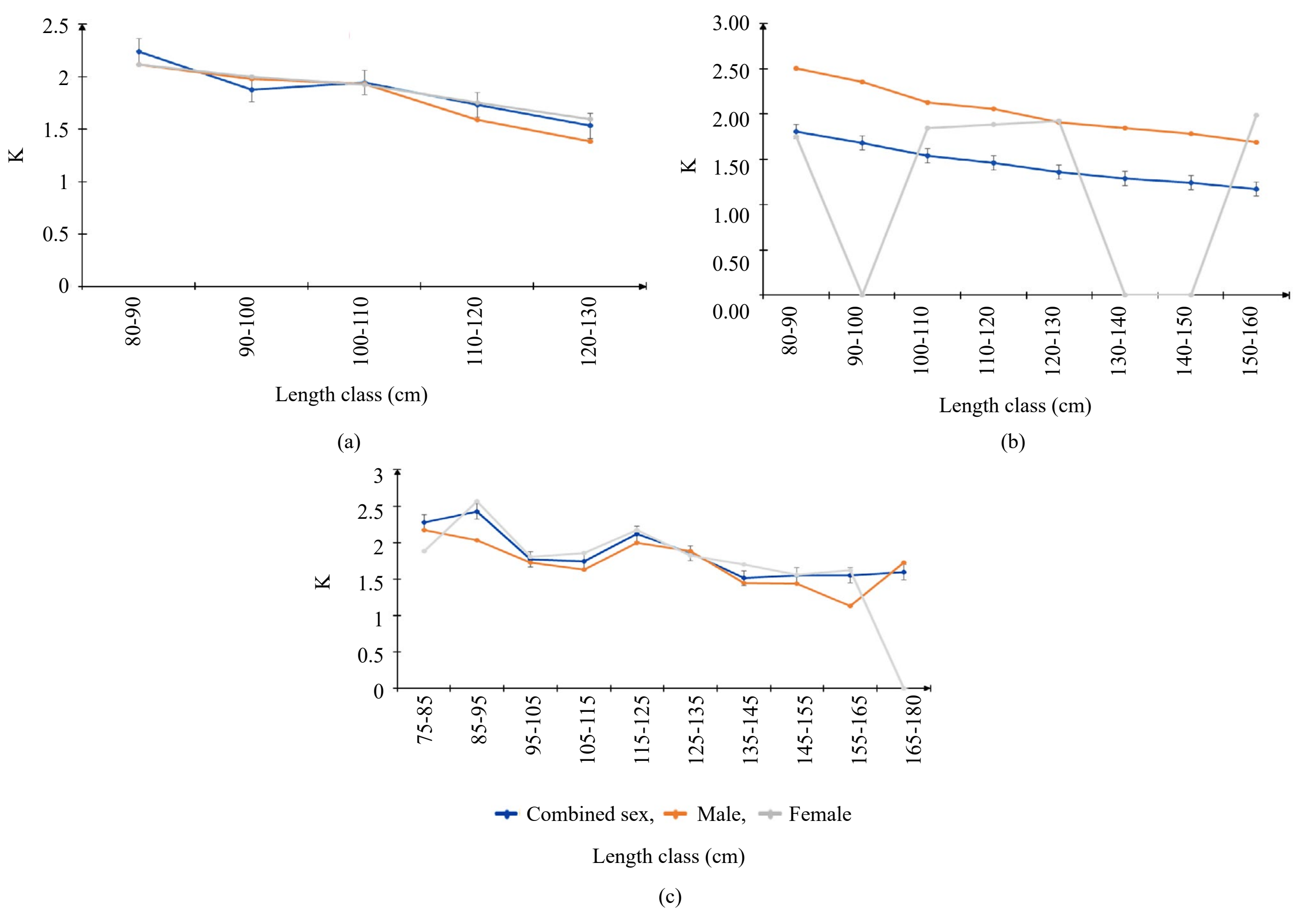

Fig. 4. Fulton's condition factor (*K*) per fork length (cm) class of (a) Albacore tuna, (b) Yellowfin tuna and (c) Bigeye tuna

Table 3. Mean±standard deviation of Condition factor (K) and Relative condition factor (K_{rel})

Species	Parameters	Range of K	Range of K_{rel}	Mean ± SD K	Mean ± SD K_{rel}
Albacore tuna	Combined sex	1.38-2.74	0.78-1.41	1.92±0.15	1.01±0.08
	Male	1.38-2.74	0.8-1.43	1.89±0.22	1.01±0.08
	Female	1.55-2.27	0.69-1.03	1.92±0.15	0.87±0.15
Yellowfin tuna	Combined sex	1.17-1.84	0.81-1.89	1.41±0.18	1.34±0.01
	Male	1.68-2.56	0.71-1.32	2.04±0.31	0.95±0.12
	Female	1.75-1.99	0.8-1.34	1.88±0.24	1.02±0.06
Bigeye tuna	Combined sex	1.04-3.58	0.65-1.67	1.74±0.42	1.02±0.06
	Male	1.04-2.77	0.64-1.39	1.67±0.51	0.96±0.1
	Female	1.13-3.58	0.68-1.61	1.87±0.26	0.99±0.09

K values of females were greater than those of males for all fork lengths except for the fork length range of 75-85 and 125-135 cm; where they were lower (Fig. 4). These results suggest that the population structure of the three species can be divided into two stages (growth stage and old stage), which aids in investigations into the sensitivity of older fish to environmental conditions (Shaofei *et al*., 2015). Therefore, it can be suggested that b values should primarily be used to evaluate growth rates because of the high growth rate during the growing stage. Conversely, K values should be used to assess the sensitivity of fish to environmental factors or health conditions. In addition, albacore tuna had higher K values than the two other species, and yellowfin tuna had a greater average K_{rel} value, indicating that the albacore specimens caught had thicker bodies than yellowfin and bigeye tuna of the same length range.

This study analysed the CPUE, size frequency, LWR, relative condition factor and Fulton condition factor for catches of albacore, yellowfin and bigeye tuna of the eastern Pacific. The results showed that CPUEs of albacore, yellowfin and bigeye tuna ranged between 1.6 and 9.82; 1.07 and 2.66 and 1.06 and 3.45 fish per 1000 hooks, respectively. In addition, the results of the LWR for the three fish showed a negative allometric growth pattern as indicated by the growth coefficient ($b<3$) and positive allometric for the females of albacore and yellowfin tuna. Moreover, the three species were in good condition, as indicated by the calculated condition factor ($K>1$).

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