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Length–Length and Length–Weight Relationships of Pacific Saury, *Cololabis saira* (Scomberesocidae), in the Northwestern Pacific Ocean

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Abstract—This study is the first to record Pacific saury's length–length relationships for converting various body length measurements from various fishing countries in the North Pacific Fisheries Commission. Also, we determined the length–weight relationship of the 2021 saury to compare with historical data. Neither age nor sex has a significant effect on the length–length and length–weight relationships. The length–length relationships were: fork length = 0.292 + 0.998 knob length (R^2 = 0.999) and standard length = – 0.464 + 0.970 knob length (R^2 = 0.986). The length–weight relationship was: body weight = 3.020×10^{-4} knob length$^{3.788}$ (R^2 = 0.894). The length–weight relationship comparison results indicate that saury has gotten thinner from 2004 to 2021.

Keywords: Pacific saury, knob length, standard length, fork length, length–weight relationship

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INTRODUCTION

The relationships between length–length and length–weight of fish are useful tools for stock assessment (Froese, 2006). The importance of determining a fish's length–weight relationship (LWR) has been highlighted in numerous studies as it provides information about growth patterns, health, habitat conditions, life history, and morphological characteristics (Schneider et al., 2000; Froese, 2006). The length–length relationship (LLR) is important as it provides a way for comparative growth studies between different fish body length measurement metrics (Moutopoulos and Stergiou, 2002). The most commonly used fish body length measurement metrics are standard length (*SL*), total length (*TL*), and fork length (*FL*) (Carlander and Smith, 1945). Due to the lack of consensus on the uniform use of the length measurement metrics, it is often difficult to do comparison and analysis between data collected with different length measurement metrics (Kahn et al., 2004). Thus, LLR is required to allow the length transformation from different fish body length measurement metrics.

The Pacific saury *Cololabis saira* is one of the most commercially important small pelagic species in the Northwestern Pacific Ocean (Tian et al., 2004; Huang, 2010; Baitaliuk et al., 2013; Xing et al., 2022). The species has a broad range of distribution, ranging from the coast of Japan, the Kuril Islands, the Bering Sea, and up to the Gulf of Alaska (Watanabe and Lo, 1989; Glebov et al., 2010). A number of countries operate saury fishing fleets, including China, Japan, Russia, South Korea, Taiwan, and Vanuatu, all of which are members of the North Pacific Fisheries Commission (NPFC). Adequate conservation measures for sustainable utilization of the saury stock should be developed and employed. Examining the LLRs and LWR is one of the steps taken to better understand the saury biological state and stock structure for stock assessment.

A substantial amount of research has been conducted on different aspects of Pacific saury, such as; LWR, age structure, size group, reproduction, and migration, which most of them requires length data. (Kosaka, 2000; Huang, 2007; Fuji et al., 2021). However, so far there is no rule or consensus on the use of a uniform metric of saury body length in the NPFC. So, if the saury body length data was shared, the knob length (KnL) was used by China, Japan, and Taiwan while the *FL* was used by Russia and South Korea. The differences in saury body length metrics often make translating the length data and relative studies into a broader application difficult. Therefore, this study is the first to investigate the saury LLRs and aims to provide the saury LLRs for statistically converting from the KnL to the *FL* and *SL*, and to determine the current saury LWR for comparison with historical data.

MATERIALS AND METHODS

One hundred and ninety-nine samples of saury were randomly collected from the catch of 2 Taiwanese saury fishing vessels operating in 2021 October at around 42.5° N and 154.0° E of the Northwestern Pacific Ocean. The saury samples were caught using the stick-held dip net at a depth of around 20–30 m, immediately frozen on board, and transported to the laboratory for further analysis.

The LLR can be established with various well-known metrics, such as *SL*, *FL*, and *TL* (Carlander and Smith, 1945). In addition, KnL is a common length measurement metric for Pacific saury as it is the easiest way to measure the saury body length with the least deviation (Kimura, 1956). Three different metrics for the saury body length measurements were used:

SL—distance from the anterior tip of the longest jaw to the tip of the hypural bone (Levastu, 1965); *FL*—distance from the anterior tip of the longest jaw to the median point of the caudal fin (Levastu, 1965); KnL—distance from tip of the lower jaw and the posterior end of the muscular knob on the caudal base (Kimura, 1956).

Each of the body length measurements for saury samples was recorded to the nearest 0.1 cm. A digital balance (Shimadzu, Japan) was used to measure the saury body weight to the nearest 0.1 g. The sex of saury was determined by observing the gonad of each fish. The age of saury was determined using the age determination method with otolith (Suyama, 2002).

To investigate the LLRs, we used a general linear model (GLM) in which the independent variable was the KnL and the dependent variable was the *FL* (1) or *SL* (2). In addition, age and sex were considered as the dependent variables in the model to examine their effects on the LLRs (1), (2).

$$FL = \beta_0 + \beta_1 \mathrm{KnL} + \beta_2 \mathrm{Age} + \beta_3 \mathrm{Sex} + \beta_4 \mathrm{KnL{:}\ Age} + \beta_5 \mathrm{KnL{:}\ Sex}, \quad (1)$$

$$SL = \beta_0 + \beta_1 \mathrm{KnL} + \beta_2 \mathrm{Age} + \beta_3 \mathrm{Sex} + \beta_4 \mathrm{KnL{:}\ Age} + \beta_5 \mathrm{KnL{:}\ Sex}, \quad (2)$$

where β_0–β_5 were the regression coefficients of the linear model, respectively.

To determine the LWR, a non-linear relationship was proposed by Le Cren (1951) as the formula: $BW = a \times BL^b$, where *BW* and *BL* are the body weight and body length, respectively, with *a* and *b* are the coefficients. In our study the formula was log-transformed and the saury sex and age were added as the dependent variables in the model to examine their effects on the LWR (3).

$$\ln(BW) = \beta_0 + \beta_1 \ln(\mathrm{KnL}) + \beta_2 \mathrm{Age} + \beta_3 \mathrm{Sex} + \beta_4 \ln(\mathrm{KnL}){:}\ \mathrm{Age} + \beta_5 \ln(\mathrm{KnL}){:}\ \mathrm{Sex}, \quad (3)$$

where β_0–β_5 were the regression coefficients of the linear model, respectively.

Two historical references of saury LWRs were compared to the current study. One was obtained from Huang (2007) using saury samples from the 2004 Taiwanese catch and its LWR was $\ln BW = -6.98 + 3.55 \ln \mathrm{KnL}$. The Taiwanese saury samples were collected in late July in the high seas. The other one was from Kosaka (2000) using data from the 1950s–1980s Japanese catch and its LWR was $\ln BW = -6.50 + 3.32 \ln \mathrm{KnL}$. The Japanese saury samples were collected from July–December in the coastal waters. The comparisons of the mean body weight in the 2021 Taiwanese catch to those from the 2004 Taiwanese catch and the 1950s–1980s Japanese catch were examined using the Student *t*-test with the *t* score (*t*) and degree of freedom (*df*). Statistical analysis was performed using "stats" package in R (Ver 4.2.1) (R core team, 2021), and all statistics were considered significant at $p < 0.05$.

RESULTS

The 199 saury samples ranged from 24.10–32.70 cm in KnL and 51.00–192.01 g in body weight. The sex and age compositions of the samples were 108 females and 91 males, and 41 age 0 and 158 age 1 fish, respectively. The *FL* and *SL* of the saury ranged from 24.4–33.0 cm and from 22.8–31.6 cm, respectively.

LLRs for Saury

The relationship between *FL*–Knl is shown in Fig. 1a. Results of the ANOVA of the GLM for the saury *FL*–KnL relationship (eq. 1) showed that the variables Age ($F_{1, 193} = 2.06$, $p = 0.15$) and Sex ($F_{1, 193} = 0.23$, $p = 0.63$) and their interaction terms with the KnL (Age: $F_{1, 193} = 1.90$, $p = 0.17$; Sex: $F_{1, 193} = 0.65$, $p = 0.42$) were insignificant. Accordingly, the saury *FL*–KnL relationship was the same across the age groups and sexes, and the saury *FL*–KnL conversion equation was determined as: $FL = 0.292 + 0.998 \mathrm{KnL}$ ($R^2 = 0.999$, $F_{1, 197} = 138129$, $p < 0.001$).

The relationship between *SL*–Knl is shown in Fig. 1b. Results of the ANOVA of the GLM for the saury *SL*–KnL relationship (Eq. (2)) showed that the variables Age ($F_{1, 193} = 0.24$, $p = 0.63$) and Sex ($F_{1, 193} = 0.06$, $p = 0.81$) and their interaction terms with the KnL (Age: $F_{1, 193} = 0.03$, $p = 0.86$; Sex: $F_{1, 193} = 0.29$, $p = 0.59$) were insignificant. Accordingly, the saury *SL*–KnL relationship was the same across the age groups and sexes, and the saury *SL*–KnL conversion equation was determined as: $SL = -0.464 + 0.970 \mathrm{KnL}$ ($R^2 = 0.986$, $F_{1, 197} = 13416$, $p < 0.001$).

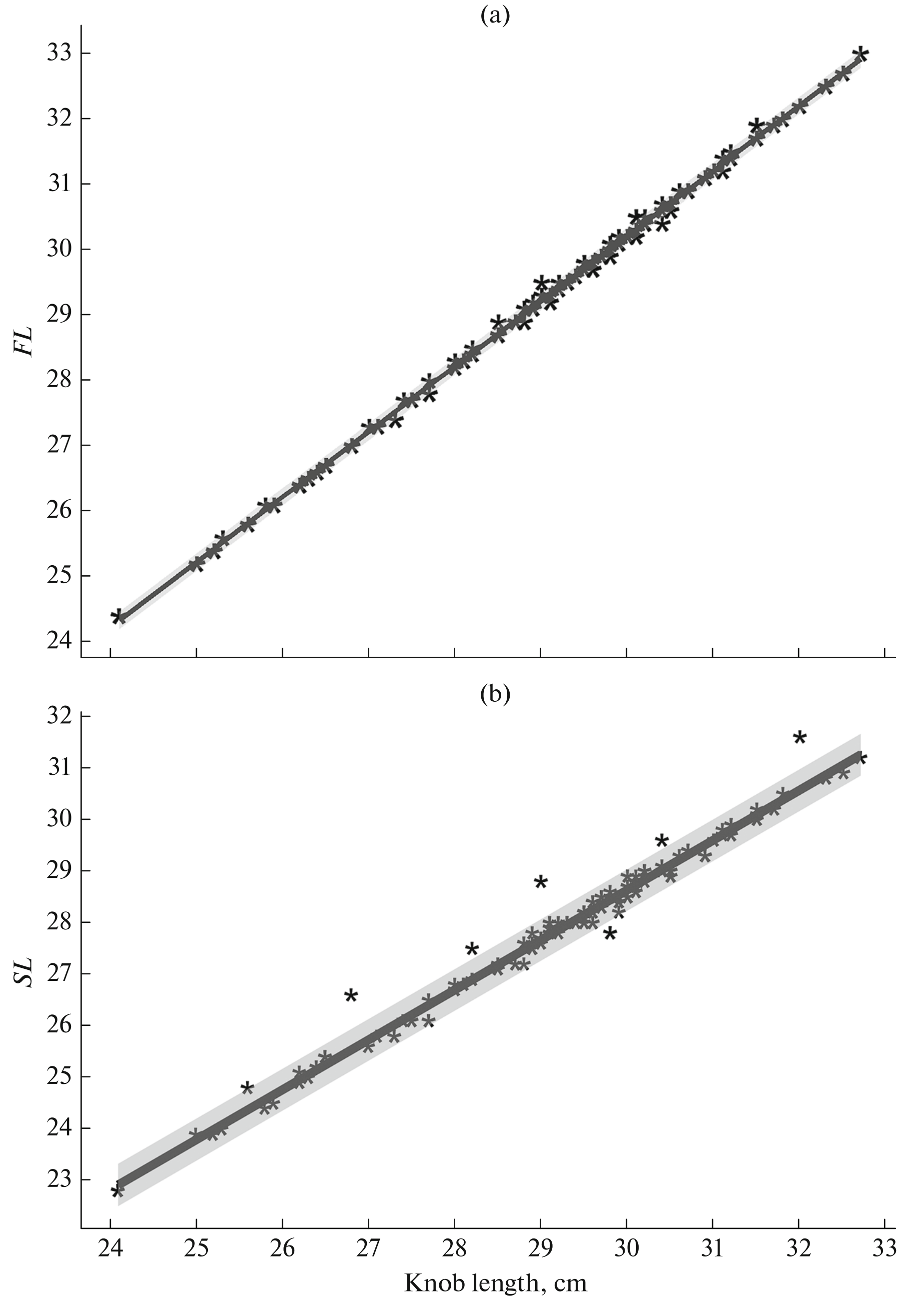

Fig. 1. A scatterplot with a regression line of the knob length and fork length (*FL*, cm) (a) and standard length (*SL*, cm) (b) of the Pacific saury: (▬) the 95% confidence interval. Here and in Figs. 2, 3: (*) observations of saury samples.

LWR for the Saury

The length–weight relationship for saury is shown in Fig. 2. Results of the ANOVA of the GLM for the saury LWR (eq. 3) showed that the variables Age ($F_{1, 193} = 0.49$, $p = 0.48$) and Sex ($F_{1, 193} = 1.22$, $p = 0.27$) and their interaction terms with the KnL (Age: $F_{1, 193} = 0.98$, $p = 0.32$; Sex: $F_{1, 193} = 0.99$, $p = 0.32$) were insignificant. Accordingly, the saury LWR was the same across the age groups and sexes, and was expressed as: $\ln BW = -8.105 + 3.788 \ln \mathrm{KnL}$ ($R^2 = 0.894$, $F_{1, 197} = 1663.90$, $p < 0.001$), or $BW = 3.02 \times 10^{-4} \mathrm{KnL}^{3.79}$.

LWR Comparison with Historical Data

The mean and standard error KnL and body weight of the 2021 saury samples were 29.28 ± 0.12 cm and 110.40 ± 1.61 g, respectively. At a given body length, 29.28 cm for example, the mean body weight in the Taiwanese 2021 catch was significantly lower than the

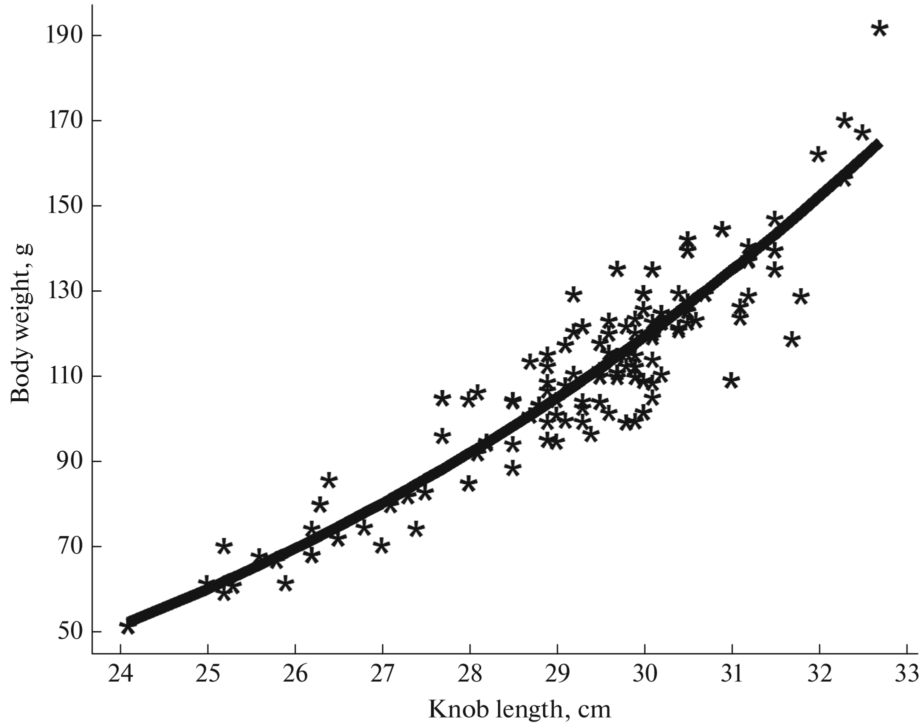

Fig. 2. Length–weight relationship of the Pacific saury.

143.61 g estimated for the Taiwanese 2004 catch ($t = -20.70$, $df = 198$, $p < 0.001$), while it was not significantly different from the 111.87 g estimated for the Japanese 1950s–1980s catch ($t = -0.92$, $df = 198$, $p = 0.36$) (Fig. 3).

DISCUSSIONS

Our results showed that the *FL* measurements had a lower variation when compared with the *SL* measurements (narrower 95% confidence interval) (Figs. 1a, 1b). The high variation in the *SL* measurements could be attributed to the individual observer's interpretation of where the caudal peduncle ends and where the hypural bone ends (Kahn et al., 2004). As for the *FL*, the obstacles to using metrics lie in the condition of the caudal peduncle of the fish, which is often damaged during handling. Generally, it is easier to observe the posterior muscular knob for the KnL measurement. Accordingly, we suggest using the KnL as the standard measure of saury body length for all of those reasons. In cases where saury KnL measurement is not the standard metric, the model presented in this study can be applied to convert length measurements to desired length measures.

Our results provide a way to transform saury *FL* to KnL and *SL* to KnL (vice versa) to overcome the difference of various body length measurements shared from various saury fishing countries for the saury stock assessment. This is the first effort to establish the relationship among various saury length measurements used by the NPFC members. Our model for length conversions can be used across the saury age groups or sexes since no significant effect of the age and sex was detected on the saury LLRs. This indicates that the growth of the saury lengths is proportionally equal.

The result from the saury length–weight relationship shows that $b > 3$. The b value would be exactly 3.0 if the fish retains its shape and specific gravity remains unchanged during its lifetime (Wooton, 1990). Fuji et al. (2021) reported that during the autumn season (August–December), the b value of saury LWR was also larger than three, therefore it supports the findings from this study. When the b value exceeds 3.0, the fish becomes heavier or also known as positive allometric growth (Ricker and Carter, 1958). Larger saury body weight growth is more important to catch weight than saury body length growth.

The comparison of the saury LWRs among this study and the past studies indicated that the current saury LWR was significantly different from that derived from the 2004 Taiwanese fishing samples in Huang (2007) (Fig. 3). The saury in the Taiwanese catch was thinner in 2021 than it had been in 2004. In addition, at the same body length, the saury caught on the high sea by Taiwanese fishing vessels was heavier than those caught in the nearshore waters by Japanese fishing vessels (Huang, 2007). However, the body weight of the 2021 saury on the high sea, at the same body length, is close to that of the 1952–1986 Japanese catch data in the nearshore waters (Kosaka,

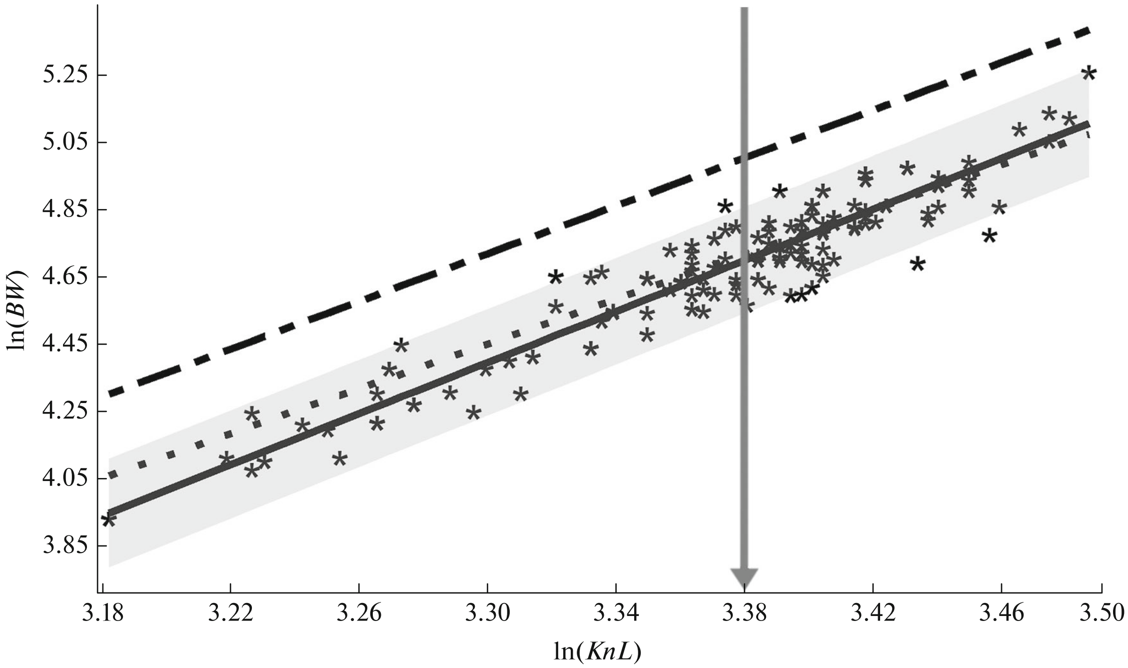

Fig. 3. A comparison of the knob length (KnL, cm) and body weight (*BW*, g) relationships (LWRs) of the Pacific saury among this study (▬) (ln*BW* = 3.788 lnKnL – 8.105) and past studies: (▬ ▪ ▬) from Huang (2007) using saury samples from the 2004 Taiwanese catch (ln*BW* = 3.545 lnKnL – 6.980) and (■ ■) Kosaka (2000) using data from the 1950s–1980s Japanese catch (ln*BW* = 3.322 lnKnL – 6.512), respectively; (↓) the length (KnL: ln 29.28 = 3.38) used for body weight comparison; the others designations see in Fig. 1.

2000) (Fig. 3). This implies that there is a decrease in the growth of the saury which could be due to environmental degradation and climate change.

Results of the stock assessment indicated the saury stock biomass had fallen to a historically low level around 2019 according to SSCPS (Small Scientific Committee on Pacific Saury, report of the 8th meeting: https://www.npfc.int/sites/default/files/2022-02/SSC%20PS08%20report.pdf). Not only is the saury population decreasing, but our results show the saury body weight has decreased as well. The decrease in the saury population is not only in the number of fish but also in the individual body weight of the fish.

It is imperative to understand the LWR when analyzing the biometric characteristics of fish populations. This information is valuable for species management and ecosystem conservation (Arshad et al., 2012). LWR can be used for predicting body weight based on body length, vice versa, as well as indicating the condition factor (Le Cren, 1951). LWR, however, is not constant throughout the year, varying seasonally according to numerous factors such as food (quantity, quality, and size), seasons, and temperature (Clarke and Fraser, 2004; Froese, 2006; Falsone et al., 2022). Fuji et al. (2021) found that the saury LWR was different among seasons. Thus, when applying the LWR and its parameters found in this study, it is important to consider the effects of growth shifts as the fishing season progresses.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interests. The authors state no conflict of interest with respect to the research, authorship, and/or publication of this article.

Statement on the welfare of humans or animals. All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

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