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Age and growth estimates from three hard parts of the spotted catfish, *Arius maculatus* (Actinopterygii: Siluriformes: Ariidae), in Songkhla Lake, Thailand's largest natural lake

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Abstract

The spotted catfish, *Arius maculatus* (Thunberg, 1792), is a euryhaline fish that is economically important in the Indo-West Pacific. Population dynamics studies and stock assessments of this species have focused on marine stocks, but not those from fresh water. In this study, the age and growth of *A. maculatus* were, therefore, investigated for the inland stock in Songkhla Lake, Thailand. A total of 213 individuals ranging between 35 and 238 mm TL were used. The length–weight relation indicated positive allometry of this population. Three hard parts (otolith, dorsal- and pectoral-fin spines) were used for aging. The marginal increment ratio confirmed that an annulus was deposited once a year in all three hard parts. All of the samples were aged between 0+ and 6+ years. Verification of age estimates from three readers showed that the otolith was the most suitable part for age estimation. Three growth models (von Bertalanffy, Gompertz, and logistic) were applied in the study. The von Bertalanffy model best described the growth of this fish in Songkhla Lake. The obtained asymptotic length was 290.87 mm TL and the relative growth rate parameter was 0.166 year^{-1}. Our results will be applied as inputs for fish stock assessment models. The obtained growth parameters also can serve as a reference for *A. maculatus* stocks elsewhere.

Keywords

Arius maculatus, Dorsal-fin spine, otolith, pectoral-fin spine, Thailand, von Bertalanffy growth model

Introduction

The family Ariidae accommodates more than 140 species of catfishes, found mainly in marine and brackish waters (Froese and Pauly 2021). However, some species are euryhaline and can live in a wide range of environments, from freshwater to marine, including the spotted catfish, *Arius maculatus* (Thunberg, 1792), which is widely distributed across the Indo-West Pacific Region (Rainboth 1996). This species has been reported to grow as large as 80 cm TL, but the typical maximum size is 30 cm TL (Froese and Pauly 2021). The trophic level of *A. maculatus* is estimated to be 3.4 ± 0.46, indicating carnivorous behavior. This fish feeds mainly on benthic invertebrates (Angsupanich et al. 2005), and plays an important role in the ecosystem; an imbalance in its abundance can trigger a trophic cascade (Froese and Pauly 2021). This fish is targeted for harvest in many countries, where the fisheries operations are mostly in either marine or brackish water environments (Arshad et al. 2008; Chu et al. 2012; Jumawan et al. 2020; Kutsyn et al. 2021). There is also a unique inland fishery for this species in Songkhla Lake, the largest natural lake in Thailand. The catch of *A. maculatus* was over 180 metric tons in 2011, following the restoration of the lake's fishery resources by declaring fish sanctuary zones and a stocking program for some indigenous species (Tanasomwang and Assava-aree 2013). The recent catch of this species in 2020 increased tremendously to 330 metric tons (Pattalung Inland Fisheries Research and Development Center, unpublished data), which was almost 1.5-fold higher than the previous record. This sharp rise in harvest implies that appropriate fisheries management of this resource is urgently required to prevent a collapse of this spotted catfish stock.

Effective fisheries management requires an understanding of the stock status and population dynamics of the targeted fish species, where the growth parameters (i.e., asymptotic length and curvature parameter) are among the crucial inputs (Isley and Grabowski 2007; Katsanevakis and Maravelias 2008). Accurate estimates of growth parameters are important for monitoring the stock status as well as for assessing management actions that have been applied to maintain the integrity of the fish stock (Zhang et al. 2020). To estimate growth, precise and accurate age data are required. Age can be estimated by several methods but counting natural growth rings of hard body parts is the most common and is generally reliable (Vitale et al. 2019). Many calcified structures, both inner parts (e.g., otoliths, vertebrae, and urohyal bone) as well as outer parts (e.g., scales, opercular bones, spines, and fin rays) have been shown to reliably reflect the age of fishes (Campana 2001; Morioka et al. 2019; Phomikong et al. 2019). As many hard parts are available for age determination, a comparison of multiple structures to determine the most suitable ones for a particular species or population is always recommended (Zhu et al. 2017). Khan et al. (2011) mentioned that selecting the most suitable hard part for aging is one of the problems in age and growth studies of fishes. They suggested comparing different bony structures of the targeted fish to obtain the most suitable one that has high precision and low aging error before further growth analysis. Moreover, if there is no significant difference in age reading between the inner and outer parts, the use of outer parts is recommended, since the fish does not need to be sacrificed; this is particularly desirable for long-lived species (Zhu et al. 2017).

Along with selecting suitable hard parts for aging, the most suitable model must be chosen for the length-at-age key, which can be determined by the shape of the growth curve and error component of the data (Zhu et al. 2017). Numerous growth curves, as well as their representative models, have been introduced and applied to explain fish growth. Growth models relate the age of fish in a population to their length or weight; the von Bertalanffy growth model is the most commonly adopted and widely used (Jones 2000; Katsanevakis and Maravelias 2008; Zhu et al. 2017). The von Bertalanffy model is commonly used because of the shape of the desired growth curve and from biological assumptions, one of which is that fish growth slows with age (Katsanevakis 2006). Other commonly used models include the Gompertz and logistic growth models (Katsanevakis 2006; Zhang et al. 2020). Both models are well suited to fishes, which exhibit low initial growth rates, but the regions above and below the inflection are asymmetrical in the Gompertz model, and symmetrical in the logistic models (Quist et al. 2012). The base assumption of all three of these models is that fish show asymptotic growth (Katsanevakis and Maravelias 2008).

The aim of this study was to provide length-at-age data and a growth model for the *A. maculatus* stock in Songkhla Lake, Thailand. We assess the suitability of hard parts for aging and evaluate three growth models to describe the relation between age and length, which can be used as a reference for other *A. maculatus* stocks. The results are also expected to be further used for stock assessment and fisheries management of the stock in Songkhla Lake for its sustainable exploitation.

Materials and methods

Study area and fish sampling. Songkhla Lake (Fig. 1) is a shallow coastal lagoon in southern Thailand (07°24′08″N, 100°15′42″E), with the mean depth of 2 m. The water body covers 1018 km^2 and is classified into three distinct zones: upper (459 km^2), middle (377 km^2), and lower (182 km^2). This lake hosts a high diversity of fishes (ca. 450 species), due in part to its range of physiological characteristics. For example, the upper zone is a freshwater environment, while the lower zone is brackish (maximum 15‰) at the mouth, where it enters the Gulf of Thailand (Damchoo et al. 2021). Meanwhile, the salinity in the middle zone fluctuates between 10‰ and 15‰ as it is a mixing zone between fresh and saline water (Tanasomwang and Assava-aree 2013). Samples of *A. maculatus* were collected from four landing sites (Fig. 1) in the upper and middle zones of Songkhla Lake (where the fishery is intensive) between January and December 2020. Individual fish were labeled, measured for standard length (SL), fork length (FL) total length (TL) to the nearest 0.1 cm, and weighed to the nearest 0.01 g *in situ*. Samples were then packed in ice and taken to the Pattalung Inland Fisheries Research and Development Center. Additionally, 15 *A. maculatus* representing various size classes were collected every three months for annual ring validation.

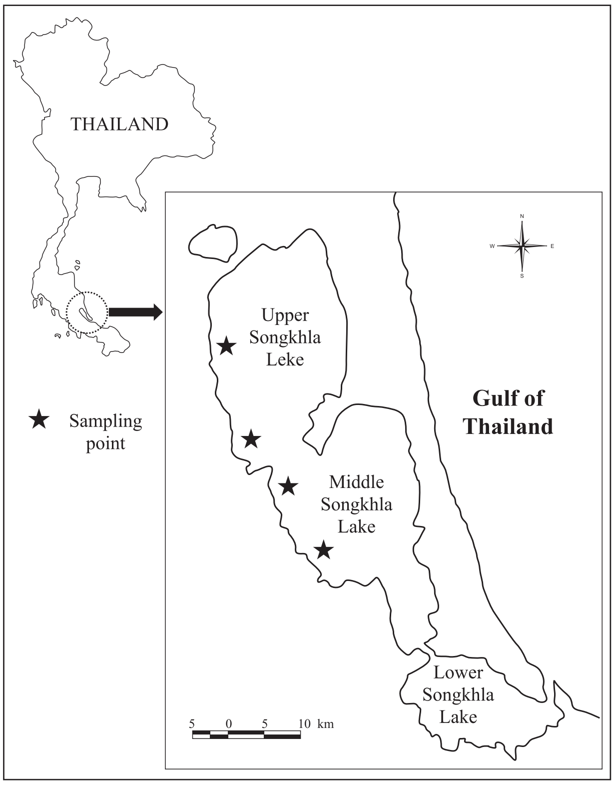

Figure 1. Location and map of Songkhla Lake, Thailand. Stars indicate fish landing points.

At the fisheries center, the largest pair of otoliths (i.e., lapilli) were removed, washed, and kept dry in a vial. Dorsal- and pectoral-fin spines were cut with bone-cutting forceps. Each hard part was embedded in resin and cut by a low-speed diamond saw (South Bay Technology Inc., model: 650). Bony parts were then polished by sandpaper (grit size ranging from 600 to 1500) until the core was seen. Each polished sample was photographed under 40× magnification, and annual rings were counted visually from the monitor and using the Image-J program. An annual ring was considered as the boundary between the inner edge of a wide opaque zone (i.e., corresponding to high growth rate) and the outer edge of a narrow translucent zone (i.e., corresponding to low growth rate) (Kutsyn et al. 2021). Three (3) readers, with no background information of the size of each individual fish, were assigned for aging each sample.

Data analysis. Length–length relations and length (TL)–weight relation (LWR) were examined by linear and curvilinear regressions. The estimated parameter "*b*" from LWR was tested for significant deviation from 3 by using a *t*-test. Annual ring formation was validated by marginal increment ratio (MIR) analysis (Beamish and McFarlane 1983) as

$$\mathrm{MIR} = \frac{(R - R_n)}{(R_n - R_{n-1})}$$

where R is the radius (distance between the center and the edge of hard part), R_n is the distance from center to outer edge of last complete band, and R_{n-1} is the distance from center to outer edge of next-to-last complete band. The difference in MIR among months of sampling was tested by Kruskal–Wallis test, and Dunn's post test was applied when a significant difference was found at $\alpha = 0.05$.

The percentage of agreement (PA) among the three readers was calculated as the ratio of the number of agreements among the three readings to the total number of readings made. Precision in age reading among the three readers of each hard part was tested by two methods (Campana 2001): mean percentage error (MPE)[1] and coefficient of variation (CV).

$$\mathrm{MPE} = \frac{\sum_{j=1}^{n} \mathrm{MPE}_j}{n}$$

where

$$\mathrm{MPE}_j = 100 \times \frac{\sum_{i=1}^{R} \frac{\left|x_{ij} - \bar{x}_j\right|}{\bar{x}_j}}{R}$$

where MPE_j is the mean percentage error for the j^{th} fish, x_{ij} is the i^{th} age estimate of the j^{th} fish, $\bar{x}_j$ is the mean age estimate for the j^{th} fish, R is the number of times that each fish was aged, and n is the number of samples.

$$\mathrm{CV} = \frac{\sum_{j=1}^{n} \mathrm{CV_j}}{n} \quad \text{where} \quad \mathrm{CV}_j = 100 \times \frac{\sqrt{\frac{\sum_{i=1}^{R}\left(x_{ij} - \bar{x}_j\right)^2}{R-1}}}{\bar{x}_j}$$

where CV_j is the coefficient of variation for the j^{th} fish. The age readings of each fish sample and each hard part from the three readers were then averaged and rounded to the nearest integer. Two additional readers with extensive experience in fish aging reviewed each hard part and checked its designated age. The age-bias plot (Campana et al. 1995) was applied to visually assess potential aging differences among hard parts. Finally, three common growth models (Duarte-Neto et al. 2012), i.e., von Bertalanffy model (von Bertalanffy 1938), Gompertz model (Gompertz 1825), and Logistic model (Ricker 1975) were fitted to the observed length-at-age data:

$$L_t = L_\infty\,(1 - e^{-k(t - t0)})$$

von Bertalanffy model

$$L_t = L_\infty e^{-e^{-k(t-t_0)}}$$

Gompertz model

$$L_t = L_\infty\,(1 + e^{-k(t - t0)})^{-1}$$

Logistic model

1 It was originally (Campana 2001) "average percent error (APE)".

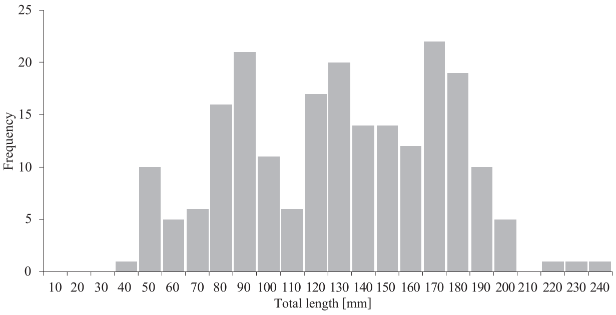

Figure 2. Length frequency distribution of *Arius maculatus* from Songkhla Lake, Thailand.

Results

A size distribution of the 213 *A. maculatus* samples used in this study is presented in Fig. 2, with a range between 35 and 238 mm TL (mean ± SD 128 ± 43 mm TL). Body weights ranged between 0.4 and 154.1 g, with mean ± SD of 26.4 ± 23.7 g. The length–length relations showed high correlation between measurements ($R^2 > 0.95$; Fig. 3A–B); meanwhile, the log-transformed LWR revealed positive allometric growth, i.e., parameter "*b*" of WLR was significantly higher than 3.0 ($P < 0.01$; Fig. 3C).

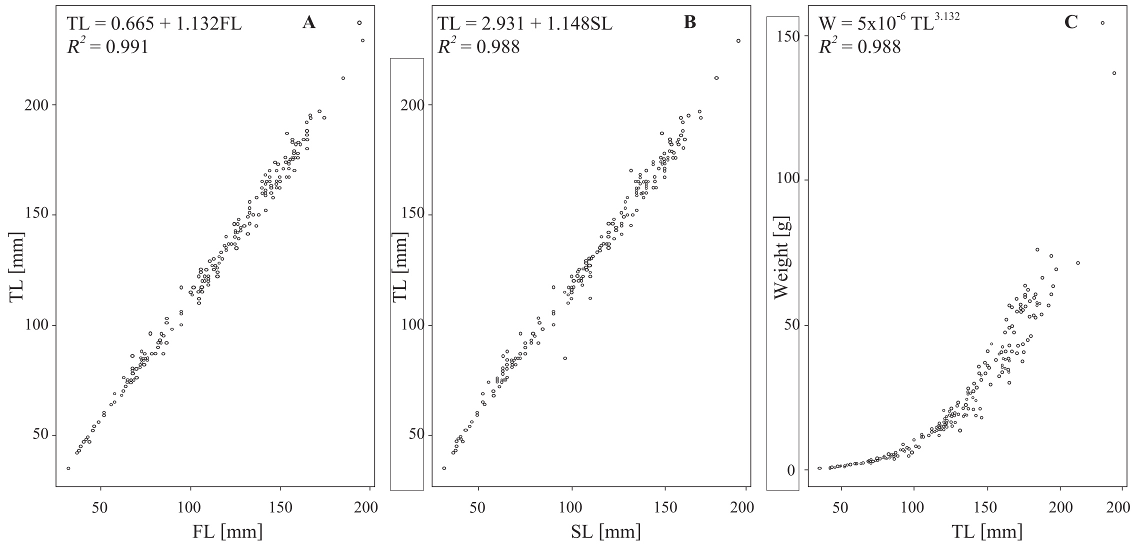

Figure 3. Length–length and length–weight relations of *Arius maculatus* from Songkhla Lake, Thailand. TL = total length, FL = form length, SL = standard length.

where L_t is the predicted length-at-age t, L_∞ is the asymptotic length, k is a relative growth rate parameter, and t_0 is the age when length is theoretically zero. The growth models were fitted to length-at-age data using nonlinear least-squares. The residual sum of squares (RSS) was used to measure the discrepancy between the data and an estimation model. The growth performance index (Ø′, Pauly and Munro 1984) of each growth model was estimated by

$$Ø' = \log(k) + 2\log(L\infty)$$

The obtained L_∞ [cm] and k values were further used to estimate the natural mortality coefficient (M) by using Pauly's equation (Pauly 1980)

$$\log_{10}M = -0.0066 - 0.279\log_{10}L\infty + 0.6543\log_{10}k + 0.4635\log_{10}T$$

where T is the annual mean water temperature, which was set at 30°C (International Lake Environment Committee Foundation 2021). Data analysis was conducted by using R-statistics (R Core Team 2020) under Package FSA (Ogle et al. 2021) and "fishmethods" (Nelson 2021).

The 60 *A. maculatus* samples for the MIR study ranged between 35 and 238 mm TL, with the mean ± SD of 128 ± 43 mm TL. The MIR results showed clear increasing trends from January (MIR near 0.5) to October (MIR near 1.0) in all three hard parts, and a significant difference was found between January and the other sampling months ($P < 0.05$; Fig. 4). The highest MIR was found in October for all hard

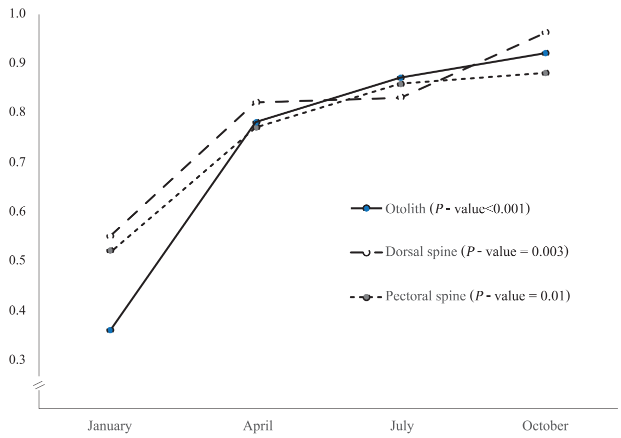

Figure 4. Marginal increment ratio (MIR) of *Arius maculatus* in Songkhla Lake, Thailand.

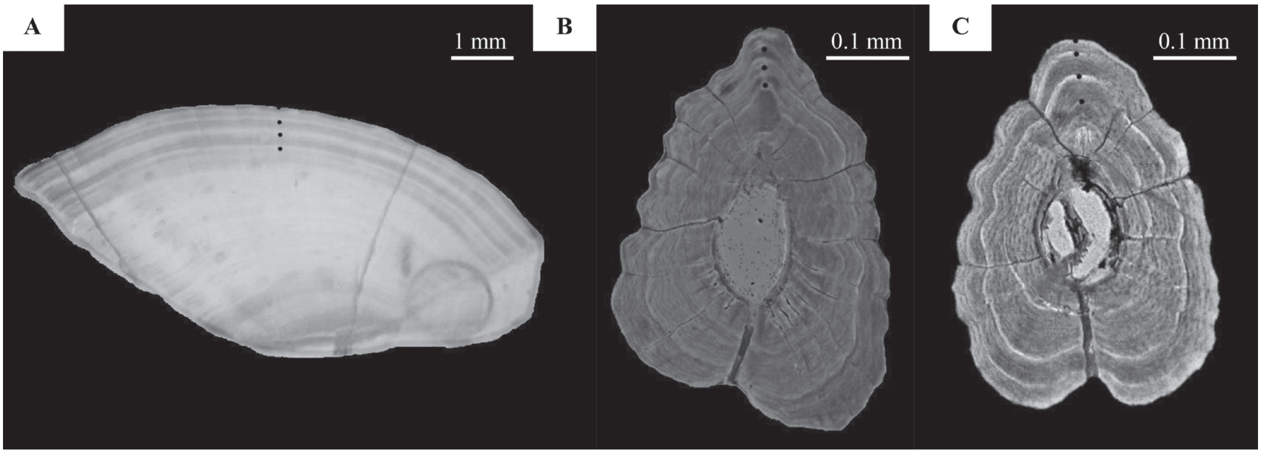

Figure 5. Cross-sections of three hard parts of *Arius maculatus* from Songkhla Lake, Thailand. (**A**) otolith, (**B**) dorsal spine and (**C**) pectoral spine. The black dots are labeled annuli.

parts and was almost double the MIR in January. The largest difference in MIR values between these two months was observed in otoliths. The significantly lower MIR in January implies that an annulus is deposited once a year.

Age estimates from the three hard parts ranged from less than 1 to a maximum of 6 years (Fig. 5). The percentage of agreement among the three readers was highest for otoliths (58.2%), resulting in the lowest MPE (9.5%) and CV (12.6%). Meanwhile, the pectoral-fin spine samples showed a higher percentage of agreement (and hence lower MPE and CV) than dorsal-fin spine samples (Table 1).

Table 1. Precision in age reading among three readers of *Arius maculatus* sampled from Songkhla Lake, Thailand.

Hard part	Agreement	MPE	CV
Otolith	58.2%	9.5%	12.6%
Dorsal-fin spine	50.3%	15.5%	16.0%
Pectoral-fin spine	55.9%	12.6%	14.4%

MPE = mean percentage error, CV = coefficient of variation.

The designated age of each hard part (i.e., by three readers in the first round) was checked by two highly experienced readers with a perfect agreement and thus was considered the observed age of each individual fish (Table 2). Biases of age reading from otoliths and spines were obvious at ages beyond 3 years, as the observed age from otoliths was a bit higher than the observed age from spines; meanwhile, less bias was found between the two spines (Fig. 6).

Parameter estimation in all models using the observed length-at-age data from the three hard parts is displayed in Table 3. It is clear that the asymptotic length (L_∞) estimated from the von Bertalanffy model (around 290 mm TL) was higher than from the other two models, for all hard parts. The larger L_∞ from the von Bertalanffy model was compensated by low k values, which consequently made Ø′ values for the three models relatively similar. The estimated natural mortality coefficient fluctuated between 0.573 and 1.631 year^{-1}, due to the estimated L_∞ and k values. In each growth model, the lowest sum of squares was obtained from the length-at-age data from otoliths. Therefore, this hard part was used to explain the growth of *A. maculatus* in Songkhla Lake as

$$L_t = 290.87(1 - e^{-0.166(t + 1.51)})$$

von Bertalanffy model

$$L_t = 229.82e^{-e^{-0.383(t-0.598)}}$$

Gompertz model

$$L_t = 209.85(1 + e^{-0.604(t - 1.274)})^{-1}$$

Logistic model

Table 2. Observed age from three hard parts of *Arius maculatus* from Songkhla Lake, Thailand.

Length (TL) [mm]	Age [year]							Total
	0+	1+	2+	3+	4+	5+	6+	
31–50	11, 11, 11							33
51–70	10, 10, 11	1, 1, 0						33
71–90	19, 20, 21	18, 17, 16						111
91–110	0, 0, 1	11, 15, 14	5, 2, 2	1, 0, 0				51
111–130		12, 13, 16	22, 20, 20	3, 4, 1				111
131–150		1, 1, 2	13, 20, 17	13, 7, 9	1, 0, 0			84
151–170		0, 0, 1	2, 8, 6	23, 22, 22	9, 5, 6			105
171–190			0, 2, 4	9, 16, 11	16, 10, 13	3, 1, 1	1, 0, 0	87
191–210				0, 2, 1	2, 2, 3	1, 1, 1	2, 0, 0	15
211–230					1, 1, 1	1, 1, 1		6
231–250						0, 1, 1	1, 0, 0	3

Note: Numbers in each cell are the observed ages from otolith, dorsal- and pectoral-fin spines, respectively.

Table 3. Growth parameters from three hard parts of *Arius maculatus* from Songkhla Lake, Thailand.

Model	L_∞ [mm]	k [year^{-1}]	t_0 [year]	RSS	Ø′	M [year^{-1}]
Otolith						
von Bertalanffy	290.87	0.166	–1.51	58,029	2.148	0.573
Gompertz	229.82	0.383	0.598	57,467	2.306	1.058
Logistic	209.85	0.604	1.274	57,472	2.425	1.463
Dorsal-fin spine						
von Bertalanffy	292.20	0.184	–1.34	65,824	2.196	0.612
Gompertz	226.19	0.443	0.507	65,267	2.355	1.170
Logistic	205.21	0.706	1.072	65,211	2.473	1.631
Pectoral-fin spine						
von Bertalanffy	286.08	0.189	–1.389	59,626	2.189	0.627
Gompertz	226.11	0.435	0.451	59,753	2.347	1.156
Logistic	206.28	0.685	1.039	60,288	2.464	1.595

L_∞ = the asymptotic total length, k = relative growth rate parameter, t_0 = age when length is theoretically zero, RSS = residual sum of squares, Ø′ = phi prime value, M = natural mortality coefficient.

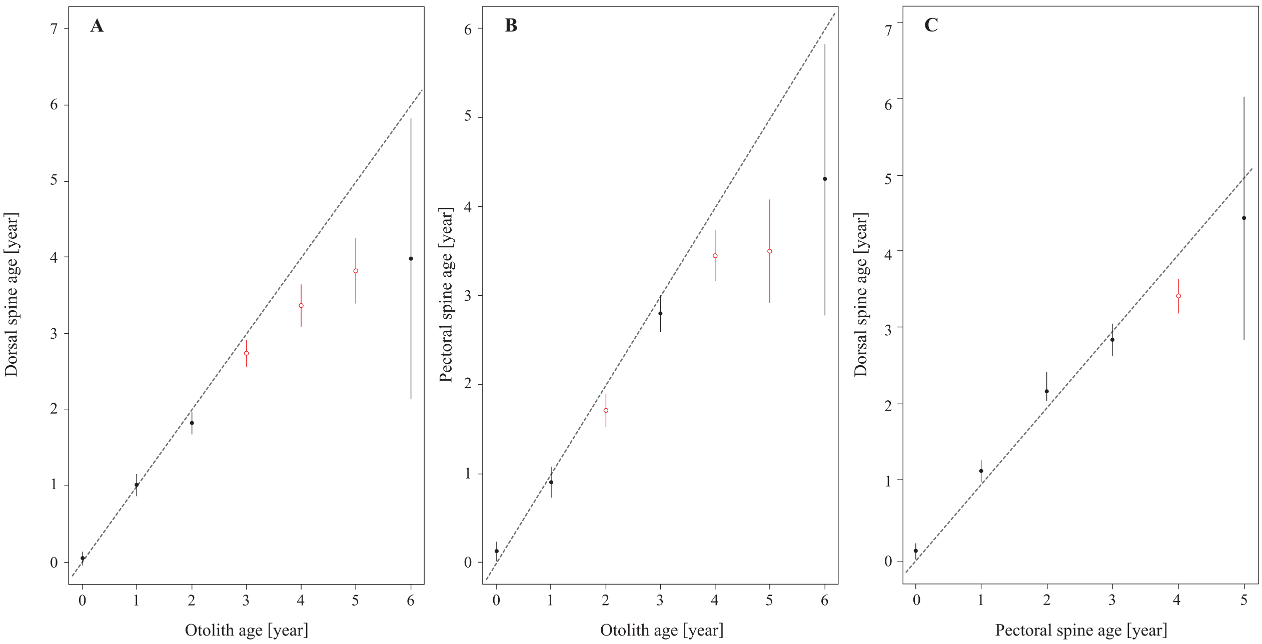

Figure 6. Age bias plots between hard parts of *Arius maculatus* from Songkhla Lake, Thailand. (**A**) otolith vs. dorsal spine, (**B**) otolith vs. pectoral spine and (**C**) pectoral spine vs. dorsal spine. Each error bar represents the 95% confidence interval.

By applying the growth curves of the three models (Fig. 7), the estimated lengths at age 1 to 5 years were almost identical, whereas the estimated sizes from the von Bertalanffy model were larger at age 6 years old and above relative to the other models.

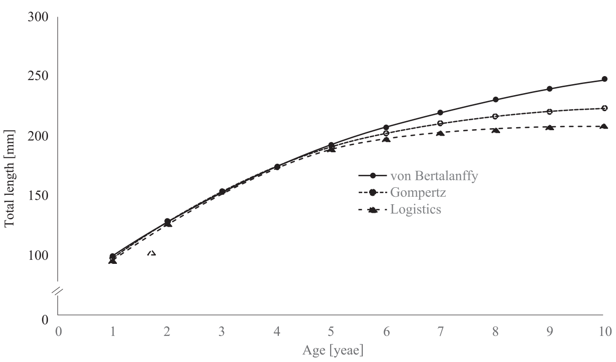

Figure 7. Growth curves of *Arius maculatus* in Songkhla Lake, Thailand, from three growth models.

Discussion

The age–length key and growth estimation of fishes and shellfishes can provide valuable insight into their life history and be further used to prescribe optimum fishing regulations for sustaining their fisheries (Isley and Grabowski 2007). In this study, the age–length key and growth of *A. maculatus* were assessed for the population in Songkhla Lake, Thailand. All the samples were from the upper or middle zones of the lake, implying that they can develop a stock in a low-salinity or freshwater habitat, contrary to the suggestion by Kutsyn et al. (2021) that this fish avoids the freshwater environment in the Mekong Delta.

The maximum length of *A. maculatus* in this study was 23.8 cm TL, which is similar to the maximum size from the Mekong Delta (25 cm TL; Kutsyn et al. 2021). Tran et al. (2021) reported that, in the Lower Mekong Basin, this fish can grow as large as 40 cm TL. The size (around 25 cm TL) found in fresh- and brackish-water habitats is substantially lower than in stocks from marine environments, such as 29 cm TL off the coast of Malaysia (Arshad et al. 2008) and 35 cm TL in Taiwan waters (Chu et al. 2012). Length–length relations showed high linearity with high correlation. The "*b*" coefficients (i.e., slope of the regression line) of SL–TL (1.15) and FL–TL (1.13) relations were similar to the values obtained for the stock off the coast of Taiwan for SL–TL (1.18) and FL–TL (1.06) (Chu et al. 2012). Meanwhile, the coefficient "*b*" for SL–TL relation of the *A. maculatus* stock from Peninsular Malaysia was 1.17 (Arshad et al. 2008). The similar values of "*b*" from various stocks indicate the similar body proportions of this fish, regardless of whether they are freshwater, brackish-water, or marine residents. The "*b*" coefficients of LWRs from this study were significantly higher than 3, indicating positive allometry (i.e., fish become heavier as length increases), and reflecting optimum conditions for growth (Froese 2006) as well as the suitability of habitat conditions (Damchoo et al. 2021). Interestingly, the "*b*" coefficients of LWRs from the marine stocks were lower than 3 (between 2.6 and 2.9) (Arshad et al. 2008; Chu et al. 2012), which could be explained either by climatic variation or resource competition (Dieb-Magalhães et al. 2015).

Age validation through MIR analysis provides relative certainty of annulus formation and confirms the growth zone deposition in *A. maculatus*. Low MIR was found in the early part of the year (January, winter) when the water temperature in the inner zone is normally less than 27°C; it is around 30°C during the rest of the year (Anonymous 2021). The maximum age (6 years) of *A. maculatus* found in this study is within the applicable range for age validation. MIR is not suitable for long-lived species or older individuals (i.e., more than 10 years) (Campana 2001). A higher percentage of agreement in aging from otoliths than with other hard parts has also been reported by other researchers (Khan et al. 2011; Zhu et al. 2017). The percentage of agreement was 50%–60% in this study. Other studies that employed only two readers achieved rates of over 60% (e.g., Khan et al. 2011; Gebremedhin et al. 2021). Although the percentage of agreement was lower in this study, verification among the three readers through MPE and CV was still lower than the upper limit of 20% (Winter and Cliff 1996; Cruz-Martínez et al. 2004). More age bias was observed between otoliths and spines (both types) than between dorsal- and pectoral-fin spines. In older fish (i.e., beyond 3 years), the higher ages estimated from otoliths could be because the spine nucleus of many fish species is reabsorbed and replaced by a hole (i.e., vascularization), which eliminates or obscures the first annulus, causing underestimation of age from spines (Drew et al. 2006; Khan et al. 2011). For this reason, together with the greater consistency in aging among the three readers, otoliths were selected for growth estimation, similar to several other studies (e.g., Khan et al. 2011; Zhu et al. 2017; Almamari et al. 2021; Gebremedhin et al. 2021) that compare ages from various hard parts.

The growth models based on the age–length key from otolith reading revealed a lower residual sum of squares than for spines, which confirms the suitability of this hard part for *A. maculatus* aging. Higher L_∞ and lower k values from the von Bertalanffy model than from other growth models have been reported in many studies (e.g., Cruz-Martínez et al. 2004; Zhu et al. 2009; Duarte-Neto et al. 2012; Zhang et al. 2020). The obtained Ø′ values from all three growth models were within the range of values from stocks of *A. maculatus* elsewhere (2.08 < Ø′ < 3.14), which were estimated either by otoliths or length-frequency data (Kutsyn et al. 2021). A suitable growth model should not only be selected by mathematical measures (Katsanevakis 2006; Katsanevakis and Maravelias 2008), but also biological as well as management points of view (Zhu et al. 2009; Haddon 2011). In a mathematical sense, the von Bertalanffy model was generally considered the most reliable candidate model for fish stocks (e.g., Zhu et al. 2009; Duarte-Neto et al. 2012; Zhang et al. 2020). From a management viewpoint, lower L_∞ and the higher k values of *A. maculatus* in Songkhla Lake from the Gompertz and Logistic models would result in an overestimated natural mortality coefficient, which would have drastic implications for fisheries management (Khan et al. 2011). For example, it could lead managers to increase fishing effort due to the high estimated natural mortality.

Conclusion

The age–length relation and growth of *A. maculatus* in Songkhla Lake, Thailand, were examined by using hard parts. Different aging structures and growth models were compared for biases in the results. Results showed that otoliths provided more precise age estimation among three readers. The von Bertalanffy model was judged to be the most suitable candidate for growth estimation because of the lowest residual sum of squares. The obtained growth parameters (i.e., L_∞ and k) can be used as inputs in other fish stock assessment models (e.g., the yield per recruit model) to investigate the optimum fishing level for this stock, which currently experiences high fishing pressure.

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