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Age, growth, and maturity of the gafftopsail catfish, *Bagre marinus*, in Northwest Florida

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AGE, GROWTH, AND MATURITY OF THE GAFFTOPSAIL CATFISH, *BAGRE MARINUS*,
IN NORTHWEST FLORIDA

By

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Abstract

The gafftopsail catfish, *Bagre marinus*, is a particularly abundant species of marine, mouthbrooding catfish found throughout the Gulf of Mexico. In this study, the age, growth, and maturity of this species was determined for a population within Apalachicola Bay, a large highly productive estuary in Northwest Florida designated as a National Estuarine Research Reserve. New age, growth, and maturity data presented for *B. marinus* is relevant as the continued exploitation of highly sought-after species in the Gulf of Mexico is likely to lead to the development of a fishery targeting *B. marinus* similar to the marine catfish fisheries of Central and South America. A total of 235 specimens were sampled in this study between April 2018 to August 2019. Age determination through use of counting the growth bands of lapillar otoliths yielded an age range of 1 to 25 years old for females and 1 to 14 years old for males. Growth was modeled with five different length-at-age models with sexes being modeled independently. Akaike information criterion corrected for a small sample size (AICc) was used to directly compare models and determine most appropriate model for the data presented. For females in this study it was found that the two three-parameter von Bertalanffy growth models ($k = 0.171 \pm 0.015$, $L_{\infty} = 515.03 \pm 7.50$ mm (fork length, FL)) yielded the best fits for the length at age data of the females with strong support also for the Gompertz model ($k = 0.217 \pm 0.016$, $L_{\infty} = 507.84 \pm 6.37$ mm (FL)). For males in this study, all models excluding the two-parameter von Bertalanffy growth model exhibited comparable fits of the data with the logistic model yielding the best fit for males ($k = 0.429 \pm 0.056$, $L_{\infty} = 470.31 \pm 11.55$ mm (FL)). Maturity ogives calculated within this study suggest that age-at-maturity was 3 years old for females and 2 years old for males. Age and growth results in this study differed from those estimated for other populations of *B. marinus* in the Gulf of Mexico.

Introduction and Rationale

Age and growth of *B. marinus* has previously been described off the Gulf Coast of Florida, however this study was conducted over two decades ago and focused on a population near Tampa (Armstrong et al. 1996). Given the two-decade time lapse between studies, it is possible that changes in life history strategies have occurred. Therefore, I believe it to be prudent to re-evaluate the age and growth of *B. marinus* in Apalachicola Bay. New life history information on *B. marinus* would allow for the modeling of this species' population dynamics, their relationship to the ecosystem as a whole, and for future fisheries targeting this species, especially when considering the relative abundance of this species in the Apalachicola Bay system. Thus, it is my intention to describe growth and maturity of *B. marinus* in Apalachicola Bay.

When compared to other teleost species, *B. marinus* exhibit a more conservative life history strategy with relatively slow growth, late maturation, a high investment into the care of offspring, and relatively low fecundity. *B. marinus* in Tampa Bay, FL were found to be slow growing, with a maximum life spans of 24 and 18 for females and males respectively, and von Bertalanffy growth coefficients (k) of 0.139 and 0.167 for females and males respectively. (Armstrong et al. 1996). Benson (1982) found *B. marinus* in the Mississippi Sound to reach sexual maturity before reaching two years of age. The spawning season for *B. marinus* was reported to occur from May through August (Jones et al. 1978). Comparably, a study done by Yànez-Arancibia & Lara-Dominguez conducted in the Southern Gulf of Mexico found that *B. marinus* spawn between April and June (Yànez-Arancibia & Lara-Dominguez 2007). *B. marinus* are a mouthbrooding species where the males orally incubate their young (Barbieri et al. 1992; Lee 1937, Pinheiro et al. 2006). Carranza & Franyutt (2005) suggested that the energetic cost of incubation could be explained by the gradual decrease in the Fulton's condition factor (a weight-

length relationship) of males in the months following spawning events (Jin et al. 2015; Carranza & Franyutt 2005). Carranza & Franyutt (2005) also found the mean number of hydrated oocytes for female *B. marinus* specimens in their study was 33, which in comparison to other teleost species is highly conservative and is a result of the mouth brooding behavior seen in most Ariid catfish species (Carranza & Franyutt 2005). Winemiller (2005) suggests that species exhibiting parental care low fecundity, and large egg size, like *B. marinus*, are classified as equilibrium-type populations that are more likely to be governed by density-dependent recruitment (Winemiller 2005).

Methods

Study Area

Sample collection was conducted in Apalachicola Bay, an estuary system in the Florida panhandle (Wilson et al. 2010). The Apalachicola Bay is semi-enclosed by three major barrier islands, Dog Island, St. George Island, and St. Vincent Island, and the drainage of the Apalachicola-Chattahoochee-Flint (ACF) River System (Livingston et al. 2000; Wang et al. 2008). The diversity and abundance of bivalve, crustacean, and bony fish species present in the bay and the bay's commercial importance for Florida fisheries has resulted in its status as a National Estuarine Research Reserve (Wang et al. 2008). The drainage of the Apalachicola River greatly influences abiotic factors such as salinity, pH, nutrient concentrations dissolved oxygen content, and currents of surrounding estuarine waters of Apalachicola Bay (Livingston et al. 2000). The flow of the Apalachicola River has also been identified as a source of variability in the abundance and relative fitness of zooplankton and phytoplankton, which form the forage base of Apalachicola Bay's ecosystem (Chanton & Lewis 1999). The trophic levels present in Apalachicola River have been directly related to perceived changes in the physical and chemical conditions in the estuary (Livingston, Niu, Lewis, & Woodsum 1997). Stable isotope analysis of

sharks and teleost fish, conducted in Florida's Big Bend region, suggests that *B. marinus* occupy a high trophic level alongside small coastal sharks (Peterson et al. 2017). This suggests *B. marinus* may play an important role in ecosystem function.

Sample Collection

Bagre marinus were collected during experimental, fishery-independent longline and gill net surveys targeting coastal sharks in Apalachicola Bay and St. George Sound, FL from April 2018 to June 2019. A total of 235 *B. marinus* specimens were captured for this study with 89 males and 146 females being represented in the sample. Specimens retained were frozen whole and processed in the laboratory.

Otolith Age Estimation

Weight and length measurements were taken for each specimen. Three length measurements were recorded; standard length (SL), fork length (FL), and total length (TL) (Morato et al. 2001; Sinovčić et al. 2004). The sex of each specimen was determined through macroscopic evaluation of the gonads. Otoliths were removed by first identifying the parieto-supraoccipital surface of the cranial roof located close to the dorsal ridge of the catfish (Aguilera et al. 2013; Arratia 2003). The parieto-supraoccipital surface was then fractured using either a claw hammer or dissecting scissors depending on the size of the catfish. After a fracture was made, the utricle was exposed from which both lapillal otoliths were extracted. The lapillal otoliths were extracted since they are the largest of the three otoliths in specimens belonging to the superorder Ostariophysi, which includes all catfishes (Long & Stewart 2010; Sánchez & Martínez 2017). Remaining tissue was removed and otoliths rinsed (Sánchez & Martínez 2017). Measurements of the length and width (mm) and weight (g) of each otolith were recorded. A one millimeter wide sagittal cross-section was taken from each otolith using a Buehler ISOMET low speed saw with a diamond encrusted blade (Jenke 2002; McCurdy 1985; Reis 1986). Cross-

sections were fixed to microscope slides using Crystal Bond 509 Clear epoxy resin. Band pairs were counted using an Olympus C011 VistaVision low-magnification microscope. (Haas & Recksiek 1994; Reis 1986). Band pairs are defined as one opaque band and one translucent band. Each band pair is assumed to represent one year of growth with a translucent band forming during rapid growth in the summer months due to warmer temperatures and increased food availability and an opaque band forming during reduced growth in the winter months resulting from colder temperatures and decreased food availability (Cermeño et al. 2006; Reis 1986; Weidman & Millner 2000). However, there was a lack of sufficient data required to validate this assumption within this study. The widest band pair seen as the first two annuli at the base of the otolith represent the first year of growth which is a period of extremely rapid development. As the fish ages, new band pairs continually become narrower (Cermeño et al. 2006; Reis 1986; Weidman & Millner 2000).

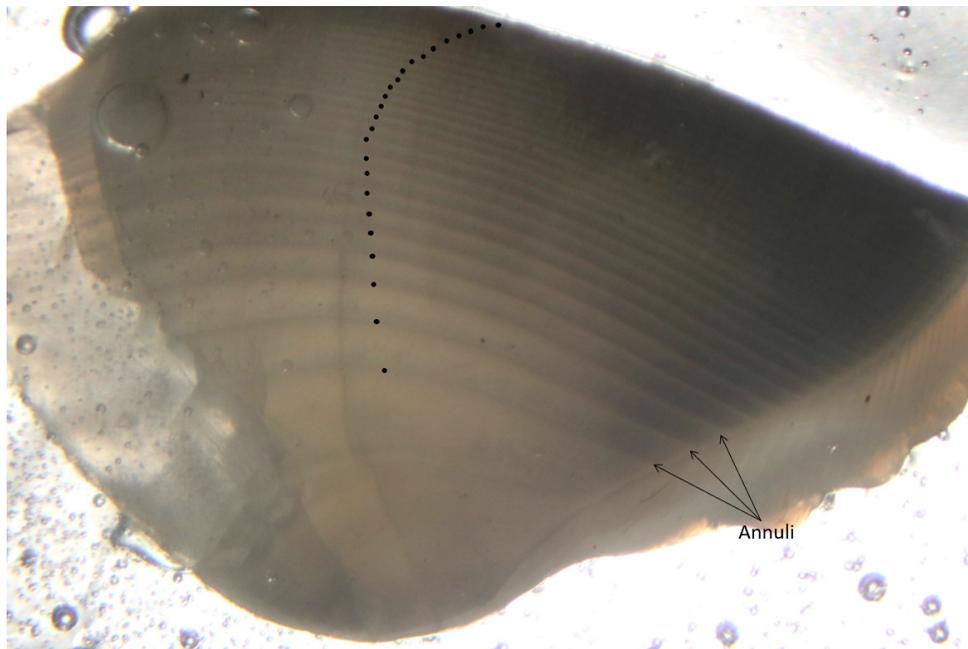


Figure 1. A sectioned otolith of *Bagre marinus* showing annuli marked with dots.

Maturity

The sexual maturity of each specimen was determined by the weight, length, and morphology of the gonads. Testes exhibited an overall longer length, shorter width, and lower weight at maturity when compared with ovaries of specimens of a similar FL and total weight (Park et al. 2004; Pinheiro et al. 2006) Maturity for males was determined by enlarged, vascularized testes or the presence of milt. Maturity for females was determined by the presence of enlarged, vascularized ovaries containing oocytes (Pinheiro et al. 2006). Maturity ogives were developed for both age and length using binomial regressions in which the inflection point of the curve corresponds to the age/length at which 50% of the fish within that age or size are mature.

Growth Models

Five methods were used to model growth and were fitted to sexes independently. In all of these models, length (L) is plotted as a function of age (t). The first three models that were used were variants of the von Bertalanffy growth model (VBGM), each with different parameters (Beverton & Holt 1957). The first VBGM used incorporated t_0 :

$$L_t = L_\infty (1 - e^{-k(t-t_0)}),$$

where L_t is the length at age t , k is the von Bertalanffy growth coefficient, L_∞ is the theoretical asymptotic length, and t_0 is the intercept on the x-axis (Beverton & Holt 1957) This model is distinguished by the abbreviation VBGF_{mod} in this study. The second model incorporated L_0 :

$$L_t = L_\infty - (L_\infty - L_0)e^{-kt}$$

Where L_0 represents the average length at age 0, L_t is the length at age t , k is the von Bertalanffy growth coefficient, L_∞ is the theoretical asymptotic length (von Bertalanffy 1939). This model is distinguished by the abbreviation VBGF in this study. The third VBGM utilized only 2 parameters and was fixed to the origin:

$$L_t = L_\infty - (L_\infty - L_H)e^{-kt}$$

Where L_t is the length at age t , L_∞ is the theoretical asymptotic length, k is the von Bertalanffy growth coefficient, and L_H is the length at age zero that was fixed at the origin (von Bertalanffy 1939). This model is distinguished by the abbreviation $VBGF_{2par}$ in this study. The fourth model used was the Gompertz model (Ricker, 1979):

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

where k_g represents the Gompertz growth coefficient (Ricker, 1979). The final model that was used was the logistic model (Ricker, 1979):

$$L_t = \frac{L_\infty}{1 - e^{-k_l(t-t_0)}},$$

where k_l is the logistic growth coefficient. The logistic model differs from the Gompertz model as the two asymptotes plotted reach the curve of the plot symmetrically (Ricker, 1979).

To determine if models should be fit to sexes separately, the residual bootstrap method was used to identify parameter estimates for $VBGM_{mod}$. The bootstrap method was run 9,999 times. The difference of means approach was then used to compare parameters between males and females. If 0 fell within the 95% confidence interval of the difference between mean parameters, the parameters were deemed to be not statistically different than one another.

Akaike information criterion corrected for a small sample size (AICc) was used to balance model fit with model simplicity in order to find the simplest and most appropriate model for the data presented (Burnham & Anderson, 2002):

$$AICc = n \log(\hat{\sigma}) + 2P + \frac{2P(P+1)}{n-P-1},$$

where P is the number of model parameters, n is sample size, and $\hat{\sigma}$ is the residual sum of squares divided by the sample size. I used $\Delta AICc$ to directly compare models. Individual $\Delta AICc$ values are calculated by subtracting the AICc value of the best model from that of the given model:

$$\Delta AICc = AICc_i - \min AICc$$

A $\Delta AICc$ of 0 indicates the best fitting model, and models with $\Delta AICc < 2$ were given strong support as being the best fitting model (Burnham & Anderson, 2002).

Results

Age Determination

The presence of false bands in some specimens presented some challenge in reading annuli however, this was only seen in a small number of otoliths. A total of 235 *B. marinus* specimens were aged, 89 males and 146 females. Age estimations ranged from 1 to 25 years in females and 1 to 14 years in males. The mean age of specimens in this study was determined to be 3 years for males and 6 years for females.

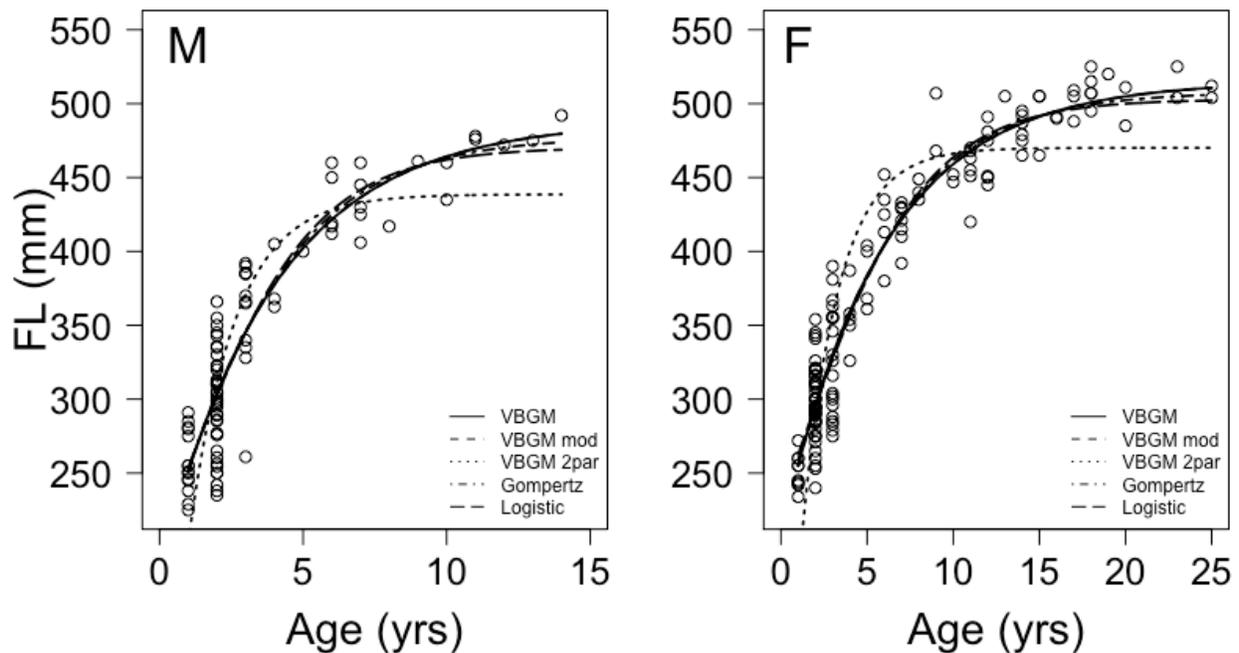


Figure 1. Plot of the length at age data, modeled independently for males (plot M) and females (plot F). For male *B. marinus*, the logistic model had the best fit of the data ($\Delta AICc = 0.00$). For the female *B. marinus*, the von Bertalanffy models incorporating t_0 and L_0 both had the best fit of the data ($\Delta AICc = 0.00$).

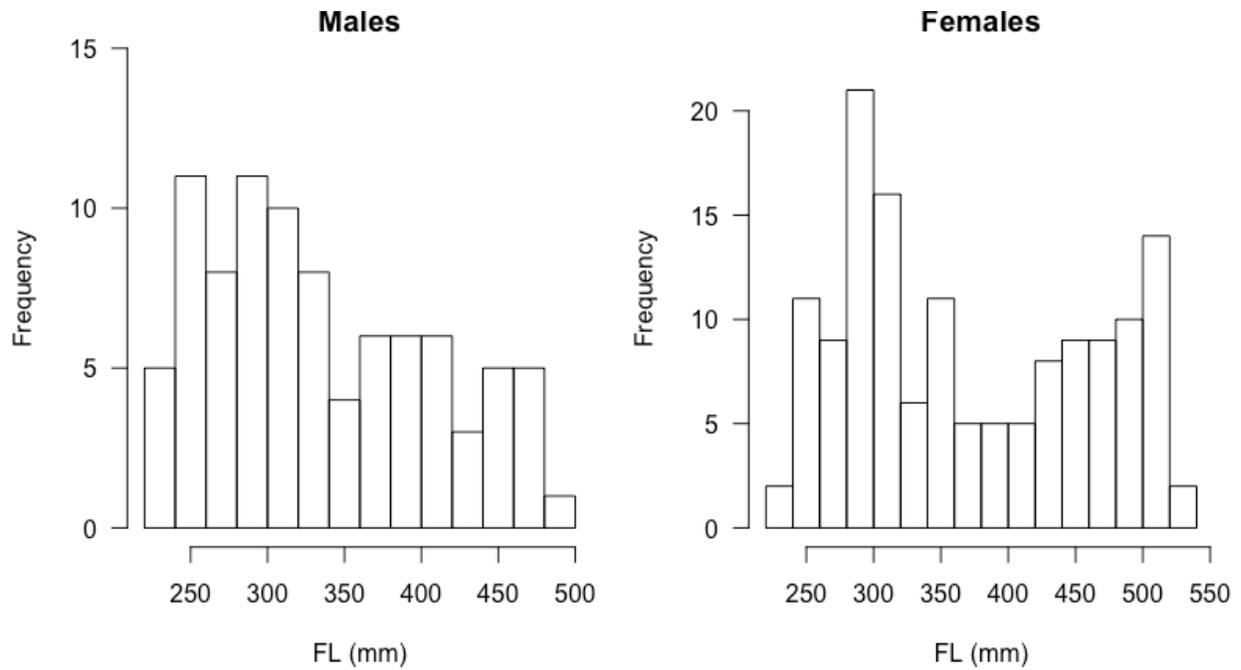


Figure 2. Histograms of the frequency of sampled *B. marinus* as it relates to fork length, modeled independently for males (n = 89) and females (n = 146).

Growth Models

A test of mean differences found the $VBGM_{mod}$ to be significantly different between sexes (Table 1), thus models were fitted to sexes independently.

| Mean Difference test | Mean Diff | LowerCI | UpperCI |
|----------------------|-----------|---------|---------|
| K | -0.0835 | -0.1387 | -0.0349 |
| L_{∞} | 24.983 | 3.827 | 40.792 |
| t_0 | -1.13 | -1.222 | -0.909 |

Table 1. Mean differences of parameter estimates between males and females. 95% confidence intervals not containing 0 indicate a significant difference between mean parameter estimates.

| Model | Sex | L_{∞} (cm) | k | L_0 (cm FL) | t_0 (years) |
|----------------------|-----|-------------------|---------------|------------------|----------------|
| VBGF _{mod} | ♀ | 515.031 ± 7.500 | 0.171 ± 0.015 | NA | -2.003 ± 0.359 |
| VBGF | ♀ | 515.030 ± 7.500 | 0.171 ± 0.015 | 149.111 ± 13.711 | NA |
| VBGF _{2par} | ♀ | 485.957 ± 4.487 | 0.303 ± 0.008 | 0.000 | NA |
| Gompertz | ♀ | 507.836 ± 6.370 | 0.217 ± 0.016 | 179.875 ± 9.100 | NA |
| Logistic | ♀ | 502.891 ± 5.691 | 0.264 ± 0.019 | NA | 1.656 ± 0.125 |
| VBGF _{mod} | ♂ | 488.418 ± 16.722 | 0.253 ± 0.042 | NA | -0.846 ± 0.447 |
| VBGF | ♂ | 488.418 ± 16.722 | 0.235 ± 0.042 | 94.314 ± 33.530 | NA |
| VBGF _{2par} | ♂ | 466.512 ± 9.458 | 0.354 ± 0.016 | 0.000 | NA |
| Gompertz | ♂ | 477.516 ± 13.383 | 0.331 ± 0.048 | 135.956 ± 19.546 | NA |
| Logistic | ♂ | 470.311 ± 11.546 | 0.429 ± 0.056 | NA | 1.629 ± 0.150 |

Table 2. Estimates of model parameters for length-at-age data for female (♀) and male (♂) *Bagre marinus*

| Model | Sex | n | p | RSS | AICc | Δ AICc | Likelihood | Weight |
|----------------------|-----|-----|---|----------|----------|---------------|------------|--------|
| VBGF _{mod} | ♀ | 146 | 3 | 78851.84 | 1341.205 | 0.00 | 1.00 | 0.392 |
| VBGF | ♀ | 146 | 3 | 78851.84 | 1341.205 | 0.00 | 1.00 | 0.392 |
| VBGF _{2par} | ♀ | 146 | 2 | 111626.3 | 1389.838 | 48.63 | 0.00 | 0.00 |
| Gompertz | ♀ | 146 | 3 | 79742.06 | 1342.844 | 1.64 | 0.441 | 0.173 |
| Logistic | ♀ | 146 | 3 | 81239.17 | 1345.559 | 4.35 | 0.113 | 0.044 |
| VBGF _{mod} | ♂ | 89 | 3 | 77915.29 | 863.99 | 0.58 | 0.748 | 0.207 |
| VBGF | ♂ | 89 | 3 | 77915.29 | 863.99 | 0.58 | 0.748 | 0.207 |
| VBGF _{2par} | ♂ | 89 | 2 | 83213.01 | 867.66 | 4.24 | 0.12 | 0.033 |
| Gompertz | ♂ | 89 | 3 | 77419.74 | 863.431 | 0.01 | 0.994 | 0.275 |
| Logistic | ♂ | 89 | 3 | 77409.21 | 863.419 | 0.00 | 1.00 | 0.277 |

Table 3. Estimates of residual sum of squares (RSS) and model selection statistics (AICc and Δ AICc) for female (♀) and male (♂) *Bagre marinus*

Male *B. marinus* grow faster and reach a shorter maximum length than females of the species, exhibiting a degree of sexual dimorphism. AICc determined that VBGF_{mod} (incorporating t_0) and the VBGF models best fit the length at age data of the females (VBGF and VBGF_{mod} both having a $\Delta\text{AICc} = 0.00$). However, the Gompertz model also fit the data well ($\Delta\text{AICc} = 1.64$). AICc determined that the logistic model had the best fit for males ($\Delta\text{AICc} = 0.00$), although relative likelihood was also high for the Gompertz model ($\Delta\text{AICc} = 0.01$) and the 3-parameter von Bertalanffy models ($\Delta\text{AICc} = 0.58$), indicating all but the VBGM_{2par} fit the data well. In both of the male and female length at age data sets AICc determined that the 2-parameter von Bertalanffy model had the worst fit for the data. This may be explained by the life history of *B. marinus* and teleosts in general where an extremely high and variable growth rate within the first year of age is exhibited and would inhibit an accurate estimate for L_0 seen in Table 3 (Houde, 1997). Theoretical maximum length (L_∞) of males and females determined by the most likely models was a range from 470-488 mm for males and 507-515 mm for females.

Maturity

Maturity was determined using a generalized linear model with a logit link function. The length at 50% maturity was calculated to be 304.854 ± 0.155 mm for females and 304.091 ± 0.177 mm for males. The age at 50% maturity was not calculated for either sex due to perfect separation of immature and mature individuals. For females, no immature individuals were found to be older than 3, while no mature individuals were found to be younger than 3. Similarly, for males the oldest immature individuals and youngest mature individuals were found to be 2 years old. Thus age-at maturity for females and males were determined to be 3 and 2 years respectively.

Discussion

The theoretical maximum lengths of males (470.311 ± 11.546 mm FL) and females (515.031 ± 7.500 mm FL) calculated by the most accurate growth models was comparable to the observed data for this study, where the maximum length seen was 478 mm FL for males and 525 mm FL for females. In my study, the oldest females were estimated to be 25 years old and the oldest males were 14 years old. Similarly, Armstrong et al. (1996) found a maximum age of 24 and 18 years for females and males, respectively. This suggested sexual dimorphism with males reaching a smaller size than females, though he did not test whether sexes should be modeled separately or together. The von Bertalanffy growth model produced by Armstrong et al. (1996) estimated similar maximum theoretical sizes to the estimates found in this study for female and males. The maximum age (14 years) was shorter and the maximum size was smaller (478 mm compared to 495 mm FL) for males recorded in this study than for the *B. marinus* population in Tampa Bay.

It was reported by Armstrong et al. (1996) that female *B. marinus* mature at 330 mm FL and that both sexes reach maturity at an age of 5 years. Length at which male *B. marinus* mature was not described by Armstrong et al. (1996). This differs from result of this study where both males and females reach sexual maturity at the same relative size of 304.854 ± 0.155 mm FL for females and 304.091 ± 0.177 mm FL for males, but at different ages, 2 years for males and 3 years for females. The differences observed in the maximum size and maturity estimates between the Tampa Bay and Apalachicola Bay *B. marinus* populations may be due to a smaller sample size and sampling distribution used in this study. Compared to this study, Armstrong et al. (1996) sampled a greater number of male *B. marinus* specimens that were larger than 400 mm FL as well as a greater number of female *B. marinus* specimens that were larger than 450 mm FL. The

frequency distribution of this study showed that a large majority of the specimens that were sampled were under 350 mm FL for males (n = 56) and under 450 mm FL for females (n =102) (Figure 1).

Furthermore, the age and growth data presented by this study also differed in relation to other studies conducted on *B. marinus* populations in locations throughout the Gulf of Mexico outside of Florida. A recent study conducted by Flinn et al. (2019) on a population of *B. marinus* in Louisiana found the maximum age observed for both male and female specimens was 10 years with no significant sexual dimorphism in size observed (Flinn et al., 2019). This variation between populations in the Gulf of Mexico may be explained by bias due smaller sample size of 93 *B. marinus* specimens total and small number of larger, older specimens of *B. marinus* analyzed. Flinn et al. (2019) included only one female individual older than 5 years and eight female specimens larger than 400 mm TL were included by Flinn et al. along with five male individuals older than 5 years and 12 male specimens larger than 400 mm TL. Differences in habitat usage between the populations may also account for the variation in age and size. Flinn et al. (2019) designated that specimens of *B. marinus* were found to inhabit the continental shelf outside of estuaries whereas in this study, specimens were collected from within the estuary itself with heavy influence from the drainage of the Apalachicola-Chattahoochee-Flint (ACF) River System as previously mentioned (Flinn et al., 2019). The distinction in specific in habitat usage described between the two populations may contribute to a disparity in the availability of resources between the two systems, leading to the observed difference in maximum age.

B. marinus is an abundant species within the Gulf of Mexico and the age of maturity, longevity, and relatively large size of this species presented by this study serve to improve future stock assessments of this species. As other fisheries in the Gulf of Mexico have become

increasingly exploited in recent decades, the fishery for marine catfish is still exceptionally small, with only 15 metric tons commercially caught in 2016 (Flinn et al. 2019). The fishery on *B. marinus* is likely to increase as the species is plentiful as previously mentioned, has a high rate of bycatch, and is already a common commercially caught fish in Mexico and South America (Carranza & Franyutt 2005; Pinheiro et al. 2006). Pinheiro et al. (2006) described the *B. marinus* fishery as the basis of gill-net fisheries throughout the northeast coast of Brazil in response to the loss of more highly sought-after species (Pinheiro et al. 2006). The next step of this study is to verify annual periodicity within this population using incremental growth analysis. This is necessary in order to quantify the rate at which males and females form growth bands and to ensure that both male and female specimens collected are depositing bands annually to validate the findings of this study.

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