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AGE AND GROWTH OF YELLOWFIN TUNA (*THUNNUS ALBACARES*) IN THE NORTHERN GULF OF MEXICO

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SUMMARY

In 2011 the International Commission for the Conservation of Atlantic Tunas (ICCAT) declared yellowfin tuna (Thunnus albacares) was undergoing overfishing but was not overfished. The 2011 stock assessment conducted through ICCAT used a two-stanza growth formulation based upon length frequency analysis (LFA) proposed by Gascuel et al. (1992) and has multiple limitations (Everhart and Youngs 1981). Age and growth information is vital to stock assessment science and is needed for greater data resolution. The 2011 assessment noted the need for gender-specific growth parameters, with the next assessment planned for 2016. Yellowfin tuna (n=1106) were aged through annual increment counts on transversely sectioned otoliths. A measurement to the first annulus was verified through daily increment enumeration. Results indicated slower growth and longer life in yellowfin tuna than previously documented [$L_t = 1597.1 * (1 - exp^{(-0.3547*(t+0.2961))})$*; CV=19.7]. Expected growth rates calculated from the growth parameters fell within the range of observed growth rates from tagged fish. Although verification is necessary, reduced growth rates for yellowfin tuna could lead to more conservative management recommendations.*

RÉSUMÉ

*En 2011, la Commission internationale pour la conservation des thonidés de l'Atlantique (ICCAT) a déclaré que l'albacore (*Thunnus albacares*) faisait l'objet de surpêche mais qu'il n'était pas surexploité. L'évaluation du stock de 2011 réalisée par l'ICCAT a utilisé une formulation de croissance à deux stances basée sur une analyse de fréquence des tailles (LFA) proposée par Gascuel et al (1992) et a de multiples limitations (Everhart et Youngs 1981). L'information sur l'âge et la croissance est capitale pour l'évaluation des stocks et elle est nécessaire pour obtenir une meilleure résolution des données. L'évaluation de 2011 a fait ressortir la nécessité de paramètres de croissance spécifiques au genre, la prochaine évaluation étant prévue en 2016. L'âge de spécimens d'albacore (n=1106) a été déterminé en utilisant le calcul de l'incrément annuel à partir des otolithes coupés transversalement. La mesure à la hauteur du premier anneau a été vérifiée en utilisant le comptage de l'augmentation quotidienne. Les résultats indiquaient une croissance plus lente et une vie plus longue de l'albacore par rapport à ce qui avait été documenté précédemment [*$L_t = 1597.1 * (1 - exp^{(-0.3547*(t+0.2961))})$*; CV=19.7]. Les taux de croissance escomptés calculés à partir des paramètres de croissance se situaient dans la fourchette des taux de croissance observés des poissons marqués. Même s'il est nécessaire de procéder à des vérifications, des taux de croissance réduits pour l'albacore pourraient donner lieu à des recommandations de gestion plus conservatrices.*

RESUMEN

En 2011, la Comisión Internacional para la Conservación del Atún Atlántico (ICCAT) declaró que el rabil (Thunnus albacares) estaba experimentando sobrepesca pero no estaba sobrepescado. La evaluación de stock realizada en 2011 en ICCAT utilizó una formulación de crecimiento en dos estanzas basada en el análisis de frecuencias de tallas (LFA) propuesto por Gascuel et al. (1992) y tiene múltiples limitaciones (Everhart and Youngs 1981). La información sobre edad y crecimiento es fundamental para la ciencia de evaluación de stock y es necesaria para una mayor resolución en los datos. En la evaluación de 2011 se indicó que era necesario

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contar con parámetros de crecimiento específicos del género y se programó la siguiente evaluación para 2016. Se determinó la edad del rabil (n=1106) mediante el recuento de incrementos anuales en secciones transversales de otolitos. La medición del primer anillo se verificó mediante la enumeración del incremento diario. Los resultados apuntaban a que el rabil tenía un crecimiento más lento y una vida más larga de lo que se había documentado previamente [$L_t = 1597{,}1 * (1 - exp^{(-0.3547*(t+0.2961))})$; CV=19,7]. Las tasas de crecimiento previstas calculadas a partir de parámetros de crecimiento se inscribían en la gama de las tasas de crecimiento observadas en peces marcados. Aunque es necesario realizar verificaciones, las tasas de crecimiento reducidas para el rabil podrían dar lugar a recomendaciones de ordenación más conservadoras.

KEYWORDS

Age determination, Growth curves, Fishery biology, Tagging, Stock assessment

Introduction

Yellowfin tuna is widely exploited across the globe both commercially and recreationally. The 2011 International Commission for the Conservation of Atlantic Tunas (ICCAT) Stock Assessment indicated overfishing is occurring but the stock is not overfished (Anon 2012). Although ICCAT assumes there is one stock of yellowfin tuna for the entirety of the Atlantic Ocean, there are multiple spawning grounds. The Gulf of Guinea is the largest of these spawning grounds, but the northern Gulf of Mexico (GOM) is an additional area of spawning (Lang et al. 1994, Arocha et al. 2000).

The largest commercial and recreational fishery for yellowfin tuna in the GOM is off the Louisiana coast. However, biological information in this region is lacking. Age and growth of yellowfin tuna has been investigated in the western Atlantic and other studies around the world (Yang et al. 1969, Le Guen and Sakagawa 1973, Draganik and Pelczarski 1984, Gascuel et al. 1992, Stequert et al. 1996, Driggers et al. 1999, Shuford et al. 2007). Despite these investigations, ICCAT has requested additional age and growth information determined by hard part analysis, preferably sex specific, from the Atlantic fisheries. Currently, ICCAT determines the catch at age from the Gascuel et al. (1992) growth relationship based upon growth between length frequency modes from year to year.

In summary, the objectives of this paper are:

1) establish an otolith "yardstick" to identify placement of first opaque increment to be interpreted as an annulus;
2) characterize age and growth of yellowfin tuna for the purpose of further informing stock assessment;
3) distinguish growth patterns between male and female yellowfin tuna;
4) use growth rates from tag recapture data to validate growth rates from age-length growth model.

Methods

Sampling

Yellowfin tuna over 68cm curved fork length (CFL) were opportunistically obtained from the recreational fishery in Venice, LA in the years 2012-2015. Whole weight and CFL were both measured in English units then converted to metric. Otoliths were removed from each fish, cleaned and stored in small plastic centrifuge tubes and inserted into a labeled coin envelope.

Yellowfin tuna under 68cm CFL were sampled with rod and reel and sent to the Fisheries Ecology Lab at Texas A&M University at Galveston for otolith extraction, processing and aging. These young fish were aged using daily increment enumeration.

Ageing

The left otolith of each fish over 68cm CFL was embedded in a 5:1 mixture of araldite and aradur (Huntsman) and sectioned transversely with a Buehler low speed Isomet saw. Sections were cut to 0.5mm thickness, mounted on a slide with Locktite UV glue and covered with Flotex mounting media. Otolith sections were analyzed and opaque increments, or annuli, counted under 25x magnification on an Olympus SZX12 dissection scope.

In an effort to evaluate accuracy and precision between laboratories and amongst readers, a joint ageing workshop was conducted in early 2015 with biologists from Texas A&M University at Galveston and Louisiana Department of Wildlife and Fisheries (LDWF). During this workshop a reference set, or sub-sample, of 50 otoliths collected in 2015 were aged independently by three readers in an effort to evaluate ageing consistencies. The first annuli was identified on each section with the aid of a "yardstick" that was developed from daily counts out to one year (Secor et al. 2014). This "yardstick" was used in determining a starting point to age each otolith by displaying the 95% confidence interval of distance for the 270th and 365th daily growth increments from the bottom of the core area (**Figure 1**).

Otoliths were aged by multiple readers (n=165), temporally separated reads from the same reader (n=336), or a single primary reader (n=555). The year 2012 otoliths (n=165) were aged by two independent readers from LDWF, while 2013 otoliths (n=336) were aged twice by a single primary reader with a pause of three months between reads. All other otoliths were only aged once by the primary reader. Average percent errors (APE) were calculated and ages between readers were compared to 1:1 relationships to determine type of bias, if present.

After aging, a measurement was taken from the bottom of the core area to the bottom of each annulus (i.e., where the increment first begins to form) at the outer and inner margin of the otolith ventral branch. Margin distance was calculated by subtracting the distance to the last annulus from the distance to the edge of the otolith. The margin value was then divided by the difference between the last annulus and the second to last annulus to create a fraction of edge growth.

The function is expressed as follows:

$$MIR = (M_d - LA_d)/(LA_d - SLA_d)$$

Where: MIR= Marginal Increment Ratio
M_d= distance to margin
LA_d= distance to last annulus
SLA_d= distance to second to last annulus

The denominator of the division equation would be different with a one, two, or three year old fish since there are such large differences between the first and second (0.53mm) or second and third (0.27) growth zones. Therefore, the denominator was the average value of distance from all measurements between the given increments (i.e. the average distance between every first and second increment). Marginal increment ratio was used in marginal increment analysis to establish the pattern of opaque increment deposition and was added to the increment count to achieve a true age.

Growth Curves

The Von Bertalanffy growth model was used to express the relationship between age and length due to its use in previous publications (Driggers et al. 1999, Shuford et al. 2007).

The function is expressed as follows:

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

Where: L_t= curved fork length at age t
L_∞= asymptotic curved fork length (theoretical maximum CFL)
k= coefficient of growth
t_0= theoretical age where CFL is 0

All statistics were completed through SAS Enterprise Guide ver 4.3.

Results

Yardstick

Daily growth increments from four fish were enumerated out to one year at Texas A&M University at Galveston. A measurement from the core was taken to the 365th daily growth increment to the outer margin (OM) and inner margin (IM) of the ventral branch of the transversely sectioned otolith. The resulting distances to the 365th daily mark averaged (±SE) 1.509mm (±0.050) to the OM and 1.077 (± 0.057) to the IM. However, it was thought that the first annuli might be more prevalent at the 270th daily growth mark, which was present 1.387mm (±0.017) from the core on the OM and 0.985 (±0.010) on the IM (**Figure 1**). Measurements from the core of one otolith to the 730th and 1102nd daily growth marks were OM: 1.843 and 2.209 mm respectively and IM: 1.368 and 1.733mm respectively.

While multiple measurements to the 365th increment enabled a concrete "year-1" marker for the yardstick, there was only one otolith that was measured to validate the second and third annulus mark. Regardless, the mean second and third annuli measurements were compared to these daily measurements for further validation that aging was completed correctly.

Growth Curve

Otoliths from 1106 yellowfin tuna were collected from the recreational fishing marinas in Venice, LA for aging (505 males, 594 females, and 7 unknown). Aged females ranged from 670-1981mm, and males ranged from 628-1765mm CFL (**Figure 2**). Average percent error for the 50 tuna otoliths from the reference set did not exceed 3.7% in any comparison of the three readers (**Figure 3**). The APE was 5.02% for the two readers that aged 2012 samples, while there was 3% error between the 2013 separate reads from the same reader. All of these error calculations are small considering the difficulty of reading yellowfin tuna otolith annuli, which is the same reason Secor et al. (2014) considered APEs under 10% acceptable in bluefin tuna.

Otolith edge measurements indicated the period of year most likely to coincide with opaque increment formation to be during the months of June to September. Mean marginal increment ratio (MIR) was the lowest in June at 45%, while the largest MIR was 58% in January (**Figure 4**). The most obvious dip in MIR occurred in June/July.

The annuli counted in yellowfin tuna yielded slower growth rates and a smaller growth coefficient (K) than previous estimates from daily increment enumeration (**Table 1; Figure 5**). Growth model parameters were 1597.1 mm CFL for L_∞, 0.3547 year^{-1} for K, and -0.2961 for t0 with a 19.7 coefficient of variation. Additionally, previous examinations that have used daily increments to age yellowfin tuna have exhibited a larger theoretical maximum length (L_∞), while the L_∞ calculated in this paper is more indicative of observed length in the population. The estimates of length at age calculated by previous growth models are above population maximum lengths (**Table 2**). Furthermore, the current growth relationship seemed to be sex specific as male and female yellowfin tuna Von Bertalanffy parameters were different. Male yellowfin tuna had a slightly lower growth coefficient but a larger L_∞, which displayed similar initial growth but a larger maximum size than females (**Table 1; Figure 6**).

Growth Rate

Length measurements were available from four tagged-recaptured yellowfin tuna off the Louisiana coast (**Table 3**). These individual growth rates were compared with growth rates derived from the Von Bertalanffy growth model used in this study and Shuford et al. (2007). Additionally, minimum and maximum growth rates were calculated from growth models generated from the Von Bertalanffy growth parameter confidence limits. The growth rate of fish 1 is closest to the estimated minimum growth rate while fish 3's growth rate is above the range estimated in this study and was closer to growth rates of Shuford et al. (2007). In contrast, the growth rate of fish 2 and fish 4 are close to the expected value from the current growth model. The large variability in individual growth indicates the need for a large data set to determine similarity between observed and expected growth rates.

Discussion

The 2011 ICCAT yellowfin tuna stock assessment has used a length at age relationship based upon growth shown in length frequency modes from year to year (Gascuel et al. 1992, Anon 2012). Although Shuford et al. (2007) provided size at age estimates based on daily growth increments, the ICCAT stock assessment group constructed a catch at age matrix with the two-stanza growth formulation based upon LFA proposed by Gascuel et al. (1992). Problems with estimating age from LFA include the inability to determine if multiple year classes are contained in one or more length mode or if there are underrepresented/absent age classes from the sample (Everhart and Youngs 1992). This could lead to incorrect assignment of age, which has direct implications of stock assessment to either under or overestimate yield per recruit (Tyler et al. 1989). This paper presents an age and growth relationship that reflects the morphometrics of the wild population and is consistent with verified growth models from other tuna species (Neilson and Campana 2008, Griffiths et al. 2010, Wells et al. 2013). The discovery of older individuals can lead to a more conservative management strategy that is needed for greater sustainability of the fish population (Beamish and McFarlane 1983).

Annuli were challenging to identify in tuna otoliths, with the first increment being especially difficult, which is reflected by higher APEs in younger fish for bluefin tuna (Secor et al. 2014). Thus a "yardstick" was established, much the same as it was in bluefin tuna, to help the reader identify the first increment. Once the first growth mark was identified, other annuli were more readily recognizable. Although the measurements of the "yardstick" provided in bluefin tuna aging were not available, the visual features of identifying the first annulus in yellowfin and bluefin seemed to be similar (Secor et al. 2014). Otoliths from both species are opaque from core to first annulus with a circular zone of translucence.

An average of MIR by month indicated that one opaque increment, or annulus, formed in the summer to early fall, but age validation was not conducted to verify this. Although mean MIR showed a trend of reduced edge in June and the following few months, small and large edge measurements were found in all months. Reduced edge was more common in June and July, thus resulting in a lower mean value. However, September also had a low MIR value with a large *n*. This result was not interpreted as biannual increment deposition due to the close proximity of September to the summer months and previous publications on tuna aging through otolith annuli enumeration (Neilson and Campana 2008, Griffiths et al. 2010, Wells et al. 2013, Secor et al. 2014).

Growth parameters that were generated in this paper were largely different from that of previous publications. Despite a growth coefficient that is comparable to the rest of the literature on yellowfin tuna growth, our theoretical maximum size or L_∞ is smaller. However, the L_∞ value is supposed to represent the mean size of the oldest individuals, which is not the case in any of the previous publications. Growth curves produced from otolith daily age enumeration had a larger L_∞ than the largest yellowfin tuna caught in the Atlantic or GOM (Driggers et al. 1999, Shuford et al. 2007). Griffiths et al. (2010) encountered a similar problem and found that daily age estimations could not be completed on longtail tuna (*Thunnus tonggol*) over 2 years of age without under aging. This suggests that these tuna may have been under-aged which inflated estimations of size at age and L_∞ in the model. The parameters generated from dorsal spines, tagging, and mark recapture are most similar to the growth relationship that is generated in this paper, but still contained a slightly large L_∞ (Bard 1984, Dragenik and Pelczarski 1984). Bard (1984) collected mostly juvenile fish and consequently had a length composition of reduced size. Wells et al. (2013) found that spine aging under-estimated age in older fish, which could explain the slight difference in growth estimation from Dragenik and Pelczarski (1984). Additionally, Gascuel et al. (1992) estimated a L_∞ that is representative of observed maximum size rather than mean size of older individuals. The K and t_0 seem to be reasonable estimates but LFA-based aging can hide age-classes in larger length modes and does not account for missing ages (Everhart and Young 1992). According to our growth parameter estimates, previous investigations have underestimated age in Atlantic yellowfin tuna, as was the case before annuli were validated with bomb radiocarbon in bluefin tuna (Neilson and Campana 2008).

The four growth rates generated from tagged yellowfin tuna revealed that individual growth is quite variable but similar to the predicted growth rates generated from the growth model. A larger sample size of recaptured fish will be needed to determine average growth rates in order to compare to the expected values. Growth rates that were generated from the growth model, as a comparison to tagged fish, did not match that of Shuford et al. (2007). The estimation of growth from daily ages generates faster growth rates that diminish at a slower rate with age than what is predicted with the growth parameters generated in this paper. For example, the estimations of size at age from daily ages seemed to be especially high in the older age classes. Estimations of size at age from LFA and spine-derived ages seem to be closer in size at age estimation but are not as conservative as the current proposed growth model.

Interpreting annual growth increments as opposed to daily increments in yellowfin tuna has led to estimations of longer life and slower growth rates than previously thought. Length frequency analysis based growth estimations could negate whole age classes, and spine aging is not as precise as otoliths in other tuna species (Everhart and Youngs 1981, Wells et al. 2013). Misclassification of age could under or overestimate yield per recruit, but more work must be completed to determine the proper aging technique (Tyler et al. 1989). The results presented are preliminary and improvements are planned for the future, including: extending multiple readers to entire data set, increasing sample size of daily age reads to further refine yardstick, and increasing recapture data to validate growth curve.

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Table 1. Von Bertalanffy age and growth parameters from this study in the Gulf of Mexico (GOM) alongside those same parameters from various investigations in the Atlantic Ocean. L_∞=Theoretical maximum size (asymptotic length in mm), k=Growth coefficient ($year^{-1}$), t_0=Theoretical age at which length is zero (years), LFA=Length frequency analysis.

Study	L_∞	*K*	t_0	*Ocean and age and growth method*
Current	1597.1	0.3547	-0.2961	GOM-Otoliths
Male	1628.4	0.3461	-0.2382	
Female	1558.6	0.3797	-0.2573	
Shuford et al. 2007	2455.41	0.281	0.0423	Atlantic-daily enumeration
Driggers et al. 1999	2371.52	0.316	0.302	Atlantic-daily enumeration
Gascuel et al. 1992	1948	0.420	0.748	Atlantic-LFA
Draganik and Pelczarski 1984	1924	0.37	-0.003	Atantic-Dorsal Spines
Bard 1984	1965.5	0.474	0.847	Atlantic-Tagging and Vertebrate

Table 2. Average curved fork length (CFL; mm) with standard deviation (SD) for each age from each publication listed with an assumed coefficient of variation of 10. Age 1 for Gascuel et al. (1992) was calculated from the linear component of the composite model. Each publication listed represents a different method of ageing; annuli (current), daily increments (Shuford et al. 2007), length frequency analysis (Gascuel et al. 1992), and dorsal fin spines (Draganik and Pelczarski 1984).

Age (yrs)	*Current*		*Shuford et al. 2007*		*Gascuel et al. 1992*		*Draganik and Pelczarski 1984*	
	CFL (mm)		CFL (mm)		CFL (mm)		CFL (mm)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	588.6	58.9	579.3	57.9	510	5.1	596.5	59.7
2	889.8	89.0	1038.9	103.9	796.6	79.7	1007.1	100.7
3	1101.0	110.1	1385.9	138.6	1191.4	119.1	1290.1	129.0
4	1249.1	124.9	1647.9	164.8	1450.9	145.1	1486.5	148.7
5	1353.0	135.3	1845.7	184.6	1621.4	162.1	1621.8	162.2
6	1425.9	142.6	1995.1	199.5	1733.4	173.3	1715.3	171.5
7	1477.0	147.7	2107.9	210.8	1807.0	180.7	1779.8	178.0
8	1512.9	151.3	2193.0	219.3	1855.4	185.5	1824.4	182.4
9	1538.0	153.8	2257.3	225.7	1887.1	188.7	1855.2	185.5
10	1555.7	155.6	2305.8	230.6	1908.0	190.8	1876.5	187.6

Table 3. Growth rates in millimeters per month (mm/mn) of three yellowfin tuna (*Thunnus albacares*) that were tagged and recaptured off the Louisiana coast with days at liberty (DAL) displayed in brackets. Growth rates for the same lengths were calculated using the Von Bertalanffy parameters and upper and lower confidence limits from the growth determined by otolith age. Where NA is displayed, the growth rate was calculated as negative, which would not represent a truth growth rate.

Source	*810-1057.5mm*	*1010-1180mm*	*1020-1111mm*	*1130-1200mm*
Fish 1 (332 DAL)				6.54 mm/mn
Fish 2 (176 DAL)			15.77 mm/mn	
Fish 3 (124 DAL)		42.5 mm/mn		
Fish 4 (431 DAL)	17.80 mm/mn			
Current (Lang et al.)	19.38 mm/mn	14.70 mm/mn	15.67 mm/mn	12.74 mm/mn
Current Min	14.33 mm/mn	8.95 mm/mn	7.40 mm/mn	4.87 mm/mn
Current Max	28.52 mm/mn	36.96 mm/mn	NA	NA
Shuford et al. (2007)	35.55 mm/mn	31.81 mm/mn	32.53 mm/mn	30.21 mm/mn

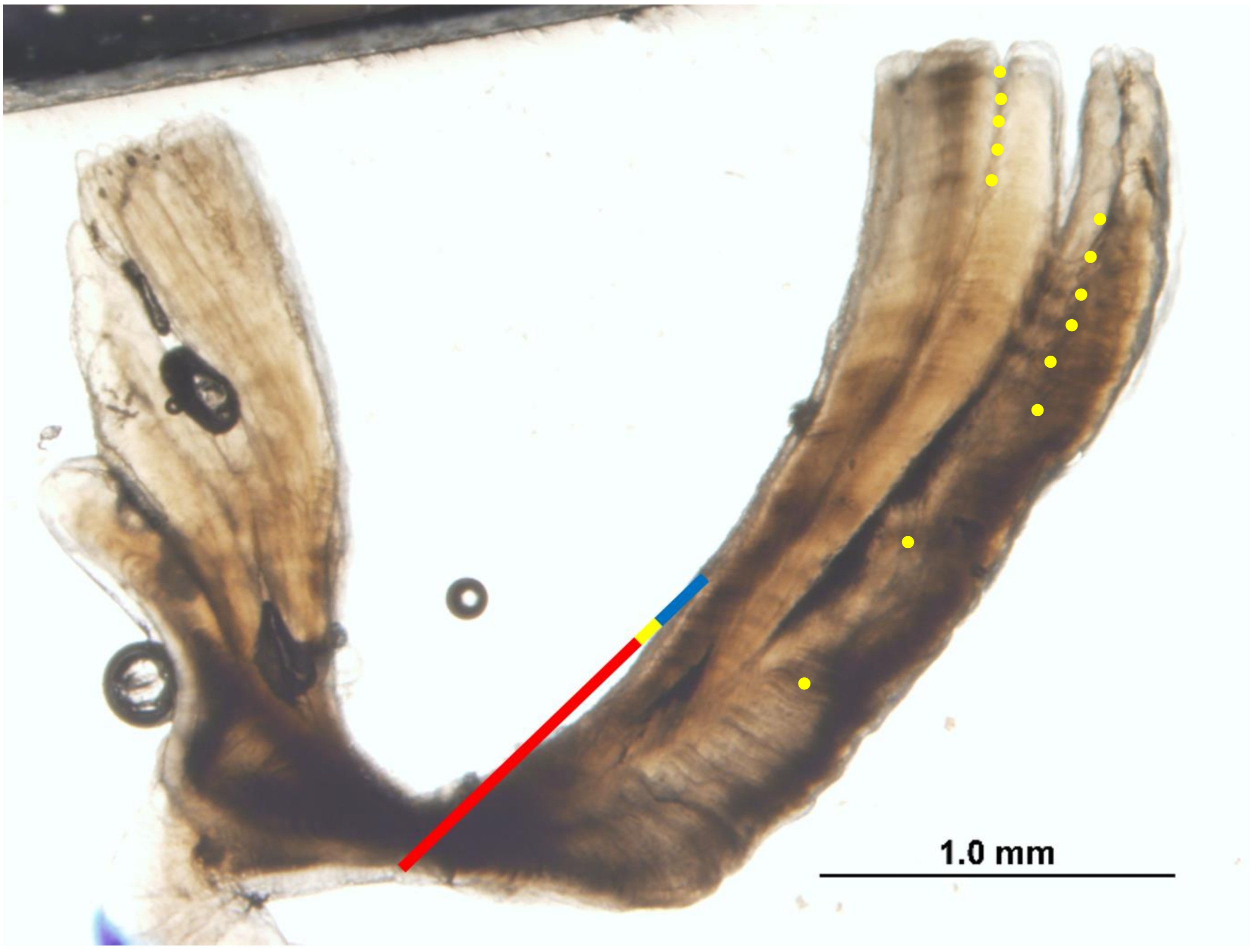

Figure 1. A yellowfin tuna transversely sectioned otolith with a "yardstick" denoting the 95% confidence interval of distance from the bottom of the core area for the 270th (yellow) and 365th (blue) daily growth marks. The red portion of the "yardstick" shows the position of the anchor when measuring from the bottom of the core zone. Each increment interpreted as an annulus is marked with a yellow dot for this 13 year old fish.

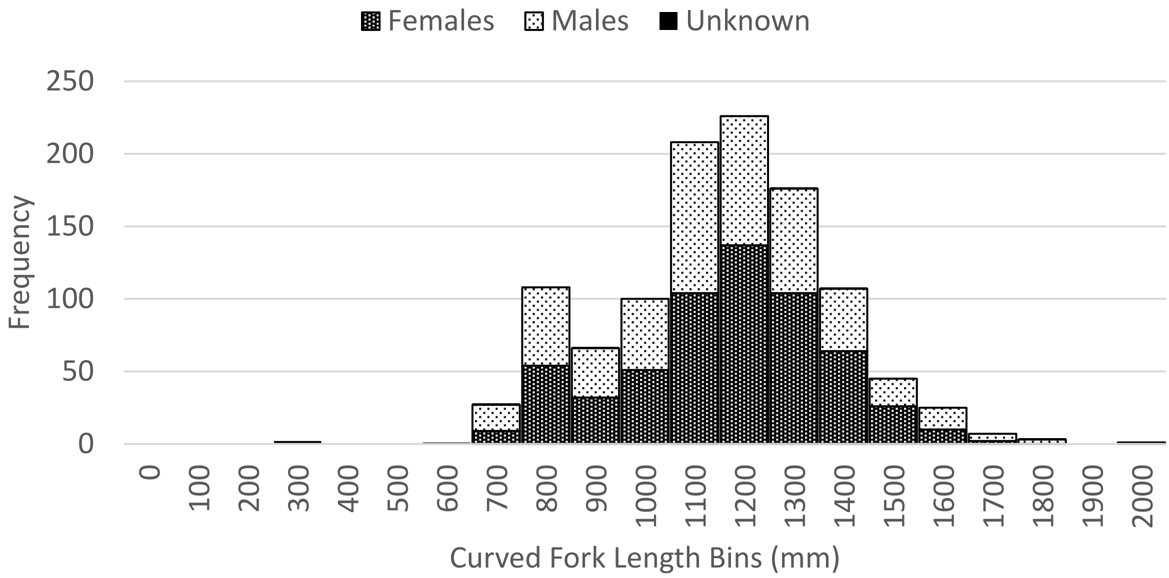

Figure 2. Curved Fork Length (mm) frequency of Male, Female, and unknown sex aged yellowfin tuna *(Thunnus albacares)*.

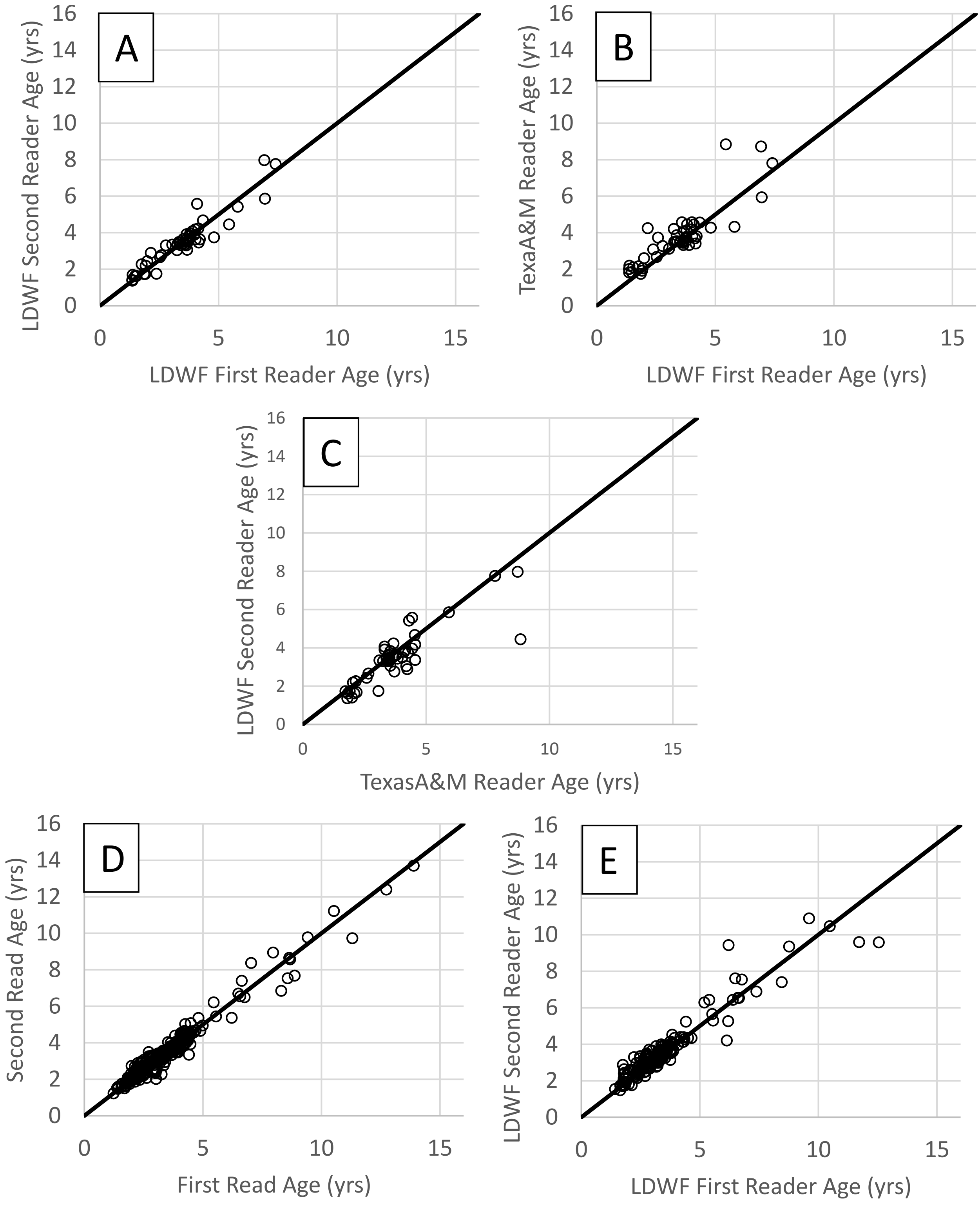

Figure 3. A comparison of ages in years for (A) 2015 reference set between two readers from Louisiana Department of Wildlife and Fisheries (LDWF), (B) 2015 reference set between LDWF reader 1 and a reader from Texas A&M University at Galveston, (C) 2015 reference set between LDWF reader 2 and a reader from Texas A&M University at Galveston, (D) 2013 otoliths read twice by the same LDWF primary reader, (E) 2012 otoliths read by LDWF reader 1 and 2.

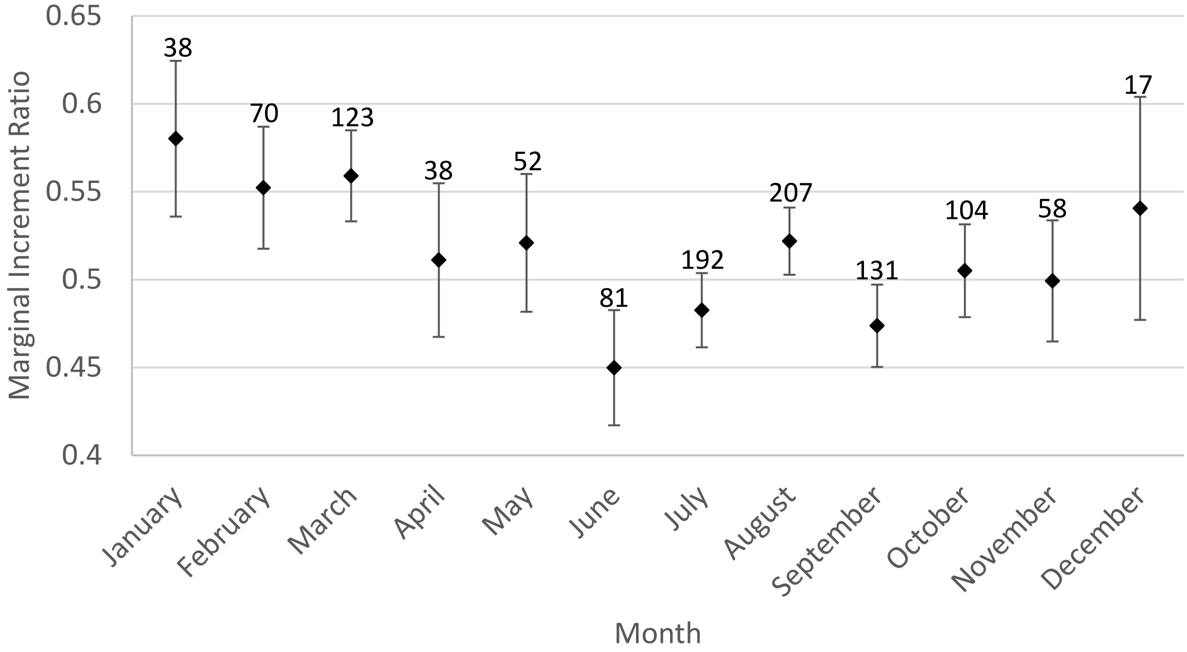

Figure 4. Marginal increment ratio of yellowfin tuna (*Thunnus albacares*) otoliths with standard error bars and sample size displayed per month over each data point.

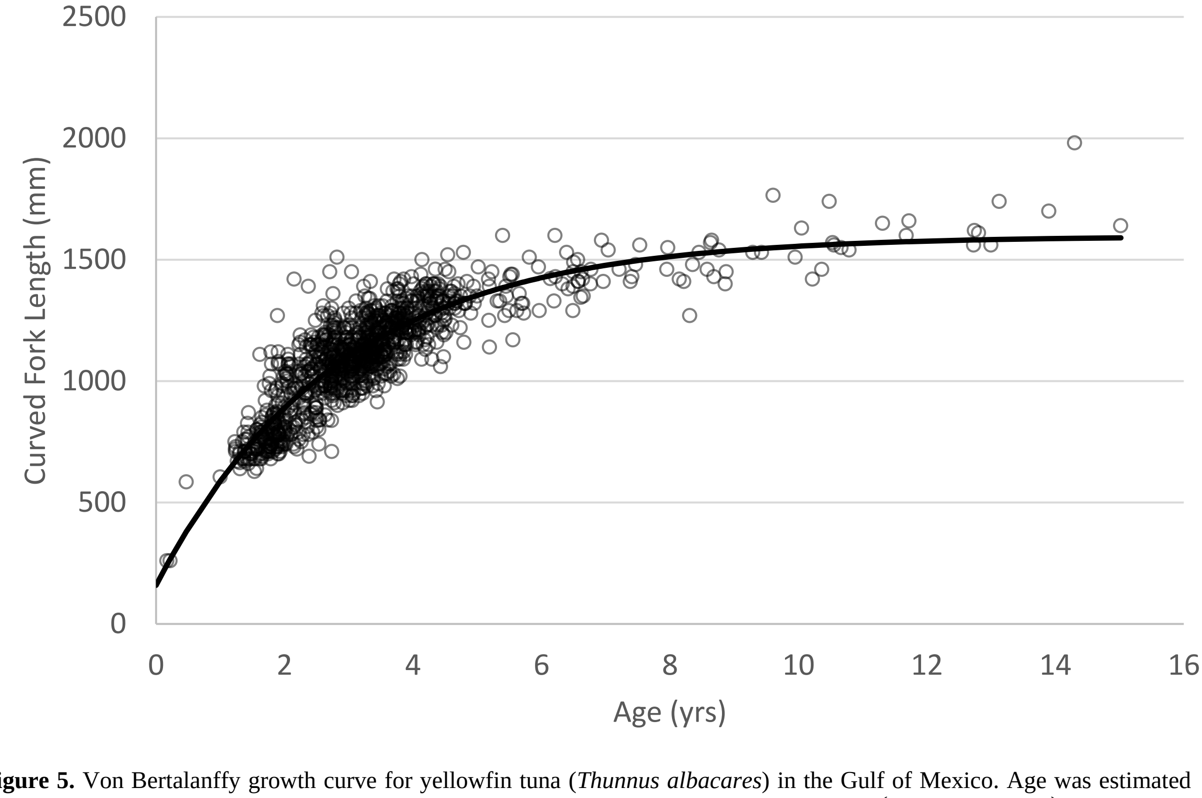

Figure 5. Von Bertalanffy growth curve for yellowfin tuna (*Thunnus albacares*) in the Gulf of Mexico. Age was estimated from annual increments. The associated Von Bertalanffy equation is $L_t = 1597.1 * (1 - exp^{(-0.3547*(t+0.2961))})$. L_t= Curved Fork Length at age t.

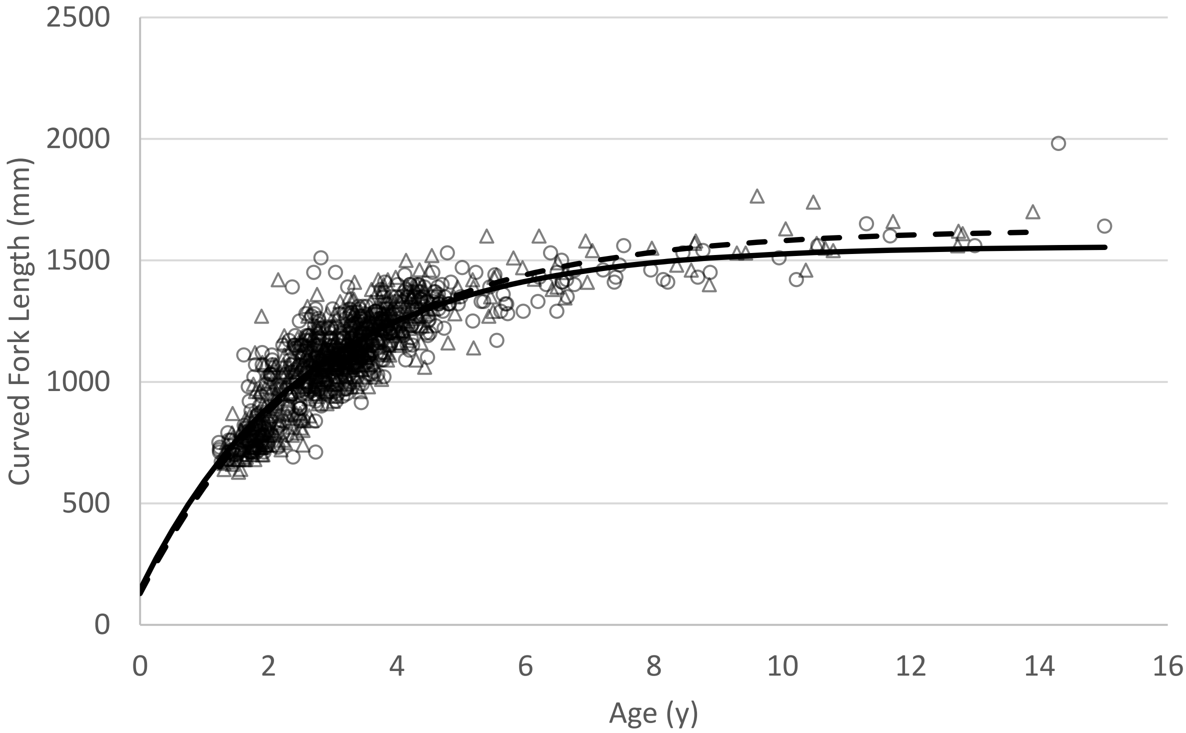

Figure 6. Von Bertalanffy growth curve for yellowfin tuna (*Thunnus albacares*) Males (Δ, dashed line) and Females (○, solid line) in the Gulf of Mexico. Age was estimated from annual increments. The associated Von Bertalanffy equation for Males: $L_t = 1628.4 * \left(1 - exp^{(-0.3461*(t+0.2382))}\right)$ and Females: $L_t = 1558.6 * \left(1 - exp^{(-0.3797*(t+0.2573))}\right)$. L_t= Curved Fork Length at age t.