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Review of current status of North Pacific albacore (*Thunnus alalunga*) age and growth

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Abstract

Accurate age and growth parameters are essential to adequately manage a fish stock. The past several North Pacific albacore stock assessments have identified age and growth as a key uncertainty. We reviewed the available age and growth data and determined that the sex-specific von Bertalanffy growth model generated by Xu et al. (2014) and currently used in the albacore stock assessment is still the best available science. We also examined patterns in mean fork length (FL) between sex, region, and year and mean length-at-age between sex and region. Male and female growth was not different up to age 5 or after age 8, however ages 8-14 strongly overlap in length, which may limit our ability to detect statistical differences at current sample sizes. Regional analyses detected overall differences in mean FL between the Western, Central, and Eastern regions, however mean length-at-age data were too patchy to determine if differences were real or an artifact of the sampling design. Annual differences in mean FL were likely a product of sampling design for the age and growth studies rather than representative of any annual variation because most years were sampled by one fishing fleet in one region. These analyses identify current data gaps and can inform research needs to improve future stock assessments of the North Pacific albacore.

Introduction

A persistent research recommendation of the stock assessment of North Pacific albacore is improved age and growth data (ISC 2011, 2014, 2017). Accurate age and growth data are critical to assigning lengths to the appropriate age class in age-structured assessment models. In 2014, Xu et al. (2014) used the data from Chen et al. (2012) and Wells et al. (2013) to calculate an updated and improved sex-specific growth model that is currently in use in the stock assessment. Two stock assessment cycles later we are still using this growth-model. Are we using the best available data? It is appropriate to periodically revisit analyses to answer this question and to identify future research needs.

The objectives of this working paper are to: 1) review available age and growth data (from Chen et al. 2012; Wells et al. 2013; Xu et al. 2014) and determine if the North Pacific albacore stock assessment is using the best available science, and 2) examine sex-, region-, and year-specific differences in mean lengths and mean lengths-at-age to assess any potential gaps in the current data.

Materials and Methods

Dataset and Modeling

Data for albacore were obtained from Chen et al. (2012) and Wells et al. (2013) and included, where available, estimated age (year), fork length (FL, cm), sex, fishing fleet, and sampling date and region (Western, Central, and Eastern). Estimated age was available as discrete age classes (Age) and as a decimal incorporating date of birth and date of collection (Adjusted Age). Adjusted Age was used for growth modeling as it was used by previous studies of North Pacific albacore (Chen et al. 2012; Wells et al. 2013; Xu et al. 2014) and produced better fitting growth models than discrete age classes (K. James unpubl. data). Lengths-at-adjusted age were fit to a von Bertalanffy growth model using non-linear least squares in R (R Core Team 2017). Model and model parameters are as explained in Xu et al. (2014). Using data from both studies three models were fit: sex-specific, sexes combined excluding fish of unknown sex, and sexes combined including fish of unknown sex. Models were compared using Akaike's criterion for small sample size (AIC_c; Burnham and Anderson 2002).

Sex-specific Analysis

Mean length-at-age and standard deviation were calculated for each discrete age class for males, females, and sexes combined. Sexes combined were first analyzed with fish of unknown sex then again without fish of unknown sex. These two scenarios were compared for each age class using ANOVAs. Sex-specific differences of length-at-age for each age class were examined with ANOVAs and Tukey's honest significance difference (HSD) analysis.

Regional and Annual Analysis

To better understand patterns in albacore size and age across the Pacific Ocean and through time, regional and annual analyses were performed. Mean FL of sampled albacore were compared across regions and years with ANOVAs and Tukey HSD analyses with fish of unknown sex and again without fish of unknown sex. Mean length-at-age of discrete age classes were also calculated between regions (including fish of unknown sex) and between sexes within regions (Central and Western only since the Eastern region lacked sex data) and compared with ANOVAs.

Results

Dataset and Modeling

The data were collected from 1990 to 2012 and varied in many respects. Chen et al. (2012) collected 273 fish predominately from the western Pacific (n = 245) by two Taiwanese longline fleets from 2001-2006 and a Japanese pole and line fleet in 2006 and 2007. Chen et al. (2013) also collected samples from the central Pacific (n = 28) by a Taiwanese longline fleet in 2002. All 273 fish were sexed. Wells et al. (2013) collected 486 fish from predominately from the eastern Pacific (n = 295) by the U.S. eastern Pacific surface fishery fleet from 2007-2010; all of these fish were of unknown sex. Wells et al. (2013) also collected fish from the central and western Pacific. In the central Pacific, albacore (n = 142) were landed by a US deep longline fleet in 1990, 1991, 1993 (n = 36 fish of known sex), 2010 and 2011 (n = 65 fish of unknown sex), and by a Japanese longline fleet in 1998 (n = 41 fish of known sex). In the western Pacific albacore (n = 49 fish of known sex) were landed by a Japanese longline fleet in 1997, 1998, and 2012.

A reanalysis of length-at-adjusted age data resulted in the exact same parameter estimates for a sex-specific model as Xu et al. (2014), however we also present a sexes combined model that differs from Xu et al. (2014) (Table 1). Xu et al. (2014) averaged the sex-specific models from Chen et al. (2012) to generate a sexes combined model then added this to the Wells et al. (2013) sexes combined model. Here we fit a von Bertalanffy growth model to the sexes combined length-at-adjusted age data. The sex-specific models (Figure 1) fit the data better than the two other models: 1) a sexes-combined model with all of the length-at-adjusted age data from Chen et al. (2012) and Wells et al. (2013) and 2) a sexes-combined model excluding fish of unknown sex (Table 2). The sex-specific model included all of the fish from Chen et al. (2012) (n = 273) and those fish of known sex from Wells et al. (2013) (Central n = 77 and Western n = 49). This means the model only included albacore from the western and central Pacific, all eastern Pacific fish were excluded because they were of unknown sex.

Sex-specific Analysis

Mean lengths-at-age for sexes combined with fish of unknown sex were not significantly different ($p > 0.074$) from sexes combined without fish of unknown sex except for age 12 ($p = 0.008$) where including fish of unknown sex decreased the mean length. Note that there were no females older than 11 in the combined database. Mean lengths-at-age for sexes combined without fish of unknown sex are presented (Table 3).

Sex-specific mean lengths-at-age (excludes fish of unknown sex) were significantly different between sexes only for ages 6 and 7 ($p > 0.001$; Table 3). Again, there are no females aged older than 11. Female mean lengths-at-age were significantly different among ages 1 through 5, while ages 5-7 were not different from adjacent age classes, and ages 8-11 were not significantly different from each other (Table 4; Figure 2). Male mean lengths-at-age were significantly different among ages 1 through 6, while 6-11 were not different from adjacent age classes, and ages 12-14 were not significantly different from each other (Table 5; Figure 3).

Regional and Annual Analysis

There was a significant difference between mean FL between region when fish of unknown sex were included ($p < 0.001$; Figure 4). The Western region had a large number of samples and covered the widest range of sizes ($n = 294$; mean = 86.6 cm FL; range 45 – 118 cm FL). The Eastern region also had a large number of samples, but no albacore over 100 cm FL ($n = 295$; mean = 77.6 cm FL; range 52.4 – 96 cm FL) and all fish are of unknown sex. The Central region represented mostly large individuals ($n = 170$; mean = 104.9 cm FL; range 67 – 128 cm). Excluding fish of unknown sex did not change mean length differences between the Western (had no fish of unknown sex) and Central region (fish of unknown sex = 65); the mean FL of the Central region did not differ if fish of unknown sex were included or excluded ($p = 0.937$). However, the maximum size of a fish of known sex in the Central region was a male at 123.2 cm FL.

Many region and age combinations did not have high enough samples sizes to be compared. Mean length-at-age was different between regions for age 3 where fish from the Eastern region were smaller than fish from the Western region ($p = 0.009$, Eastern mean (s.d.) = 73.4 cm FL (3.6), Western mean (s.d.) = 76.4 cm FL (6.2)). The following region and age combinations had insufficient sample sizes ($n < 3$) and were not analyzed: Central Ages 1, 2, 4, and 8, Eastern Ages 6-14, and Western Ages 12-14. For all other region and age combinations mean lengths-at-ages were not significantly different ($p > 0.056$).

Where possible, comparisons between the sexes were also made within regions. Within the Western region males and females had different mean lengths-at-age for ages 6 and 7 ($p < 0.001$). In the Central region, sex-specific data were too scarce only allowing ages 9 and 10 to be analyzed; there was no difference of mean length-at-age for ages 9 and 10 ($p > 0.400$).

Mean FL of albacore were significantly different amongst years both with and without fish of unknown sex ($p < 0.001$), however most years represent samples from only one region and one fishing fleet (Figure 5). The four exceptions are 2002 when Taiwanese longlines sampled in both the Western and the Central region, 2006 when samples came from both Taiwanese longlines and the Japanese pole and line fishery in the Western region, 2007 when the Japanese pole and line fishery sampled in the Western region and the eastern Pacific surface fishery sampled in the Eastern region, and 2010 when samples came from the eastern Pacific surface fishery in the Eastern region and the US deep longline in the Central region.

Discussion

Sex-specific growth curves from Xu et al. (2014) are still the best available science and should continue to be used in the North Pacific albacore stock assessment. However, certain regions, fish lengths, and fish ages are not well represented. These growth models exclude all data from the eastern Pacific and some large fish from the central Pacific due to the difficulties of sex determination experienced by Wells et al. (2013). At this point the most recent length-at-age data being used for the stock assessment is from 2012 while the rest of the samples were collected in 2007 and earlier. This highlights a need for new sampling moving forward.

With sex-specific growth curves, we expected to see differences in mean length-at-age between sexes for mature individuals (>85 cm FL, 5+ years old: Chen et al. 2012). Differences were only detected for ages 6 and 7 (Table 3). It is likely that differences were not detected for ages 8-11 because the lengths at these ages have strong overlap among age classes. Based on this dataset it is still evident that males grow larger and older than females since there are no females >107 cm FL or older than 11 years. However, larger females may exist as evidenced from size composition data from Japanese research vessels that document landings of females up to 138 cm FL (ISC 2017 Figure 3.6). For albacore, sex determination of large individuals is imperative for accurate estimation of growth models.

Regional differences were difficult to assess because of the nature of the data. The Western region has the widest range of sizes and ages, while the Central region suffered from low sample sizes and Eastern region lacked sex data. The Western region had the same differences in mean length-at-age between males and females as the overall ocean-wide analysis. The Central region may as well, but sample sizes were too low to effectively analyze ages other than 9 and 10. Based on low sample numbers for some ages and few sex-specific samples from the Central and Eastern region it is difficult to determine if patterns in length-at-age are real or an artifact of insufficient sampling. Region- or potentially fleet-specific sampling would facilitate region-specific analyses in the future.

Differences in mean FL of albacore by year appear to be driven by fishing fleet rather than temporal differences (Figure 5). It appears any change in size or age distribution over time is masked by how these samples were collected (i.e. size-specific over few years). This analysis also reinforces the size selectivity of different fishing fleets demonstrated in size composition data from the 2017 stock assessment (ISC 2017 Figure 3.5). Potential annual differences in mean length-at-age cannot be thoroughly examined because continuous sampling across multiple years was not common. Continuous sampling was not the goal of Chen et al. (2012) or Wells et al. (2013). Futures efforts to characterize age and growth would benefit from a standardized, Pacific-wide, sampling plan.

We included a sex-combined model generated by fitting a von Bertalanffy growth model to the length-at-adjusted age data (with fish of unknown sex excluded) because it differs from the sex-combined model suggested by Xu et al. (2014) (Table 1). Xu et al. (2014) averaged the male and female models, however we did not feel that was appropriate. Averaging male and female growth models introduces sex-specific growth in a sex-combined model. The purpose of a sex-combined model is to assume growth is the same between males and females. Xu et al. (2014) made a valid point that more large males were sampled than females and a potential bias in the sampling needs to be addressed. However, size composition data from Japanese research vessels indicate landings of females up to 138 cm FL and males up to 140 cm FL (ISC 2017 Figure 3.6). We do not know the age composition of these large sizes therefore, we provide a sex-combined model assuming that large females are present in the ocean although not represented in this dataset.

The current length-at-age data are patchy with regards to region, sex, fishing fleet, and year and highlight the need for new sampling of albacore to better inform future stock assessments. Any sampling plan must be scientifically rigorous and must consider potential sampling biases, resource requirements, and define the ultimate goal of the sampling plan. The analyses performed here can inform such a sampling plan. Any new proposed sampling program requires substantial resources, both time and money, but new sampling is a logical next step to improve the stock assessment of the North Pacific albacore.

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Table 1. von Bertalanffy growth parameters from the sex-specific model and two sex-combined models. SC stands for sexes combined. The sex-combined model from this study excludes all fish of unknown sex. 95% confidence intervals are in parentheses following the parameter estimates, but are unavailable for the model from Xu et al. (2014).

Model	L_∞ (cm FL)	K ($year^{-1}$)	t_0 (year)
Female	106.6 (103.7− 109.7)	0.298 (0.262− 0.338)	-0.763 (-1.066− -0.493)
Male	119.1 (116.8− 121.8)	0.208 (0.187− 0.229)	-1.453 (-1.789− -1.146)
SC this study	117.8 (116.1− 120.2)	0.210 (0.193− 0.226)	-1.435 (-1.681− -1.204)
SC Xu et al. 2014	112.4	0.248	-1.098

Table 2. AICc results for three von Bertalanffy growth models. k is the number of parameters in each model.

Model	k	AIC_c	ΔAIC_c	Log Likelihood Estimate
Sex-specific	7	2309.9	0.00	-1147.83
Sexes combined w/o unknown sexes	4	2349.87	39.93	-1170.88
Sexes combined w/unknown sexes	4	4347.5	2037.53	-2169.71

Table 3. Mean lengths-at-age for sexes combined, females, and males. Sexes combined excludes fish of unknown sex. *Indicates a significant difference ($p < 0.001$) between female and male length-at-age.

	Sexes combined			**Females**			**Males**			
	Mean length-at-age	Standard deviation	n	Mean length-at-age	Standard deviation	n	Mean length-at-age	Standard deviation	n	
Age 1	53.7	6.683	35	52.3	5.060	14	54.7	7.538	21	
Age 2	66.5	4.332	13	65.9	4.180	7	67.2	4.792	6	
Age 3	76.1	5.777	35	75.7	5.178	15	76.4	6.303	20	
Age 4	85.0	5.192	49	85.9	5.117	26	84.0	5.200	23	
Age 5	90.6	4.942	59	90.0	4.858	32	91.4	5.022	27	
Age 6	94.7	4.445	40	92.2	3.715	22	97.7	3.223	18	*
Age 7	98.2	3.510	40	95.7	1.831	18	100.3	3.191	22	*
Age 8	101.8	2.674	14	100.4	1.967	5	102.6	2.798	9	
Age 9	103.0	3.067	24	101.9	2.546	11	103.9	3.263	13	
Age 10	106.5	4.110	30	104.6	2.371	8	107.2	4.410	22	
Age 11	109.7	2.883	25	106.6		1	109.9	2.869	24	
Age 12	113.9	1.742	20				113.9	1.742	20	
Age 13	117.1	3.258	8				117.1	3.258	8	
Age 14	119.1	5.878	7				119.1	5.878	7	

Table 4. Differences among age classes for females from a Tukey HSD analysis. Values < 0.05 are in italics and indicate significant difference.

	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11
Age 1		*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Age 2			*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Age 3				*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Age 4					*0.014*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Age 5						0.737	*0.001*	*0.000*	*0.000*	*0.000*	*0.008*
Age 6							0.277	*0.006*	*0.000*	*0.000*	*0.043*
Age 7								0.488	*0.007*	0.000	0.307
Age 8									0.999	0.834	0.963
Age 9										0.963	0.993
Age 10											0.999

Table 5. Differences among age classes for males from a Tukey HSD analysis. Values < 0.05 are in italics and indicate significant difference.

	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	Age 12	Age 13	Age 14
Age 1	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Age 2		*0.002*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Age 3			*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Age 4				*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Age 5					*0.001*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Age 6						0.905	0.356	*0.019*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Age 7							0.991	0.569	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Age 8								0.999	0.379	*0.005*	*0.000*	*0.000*	*0.000*
Age 9									0.734	*0.016*	*0.000*	*0.000*	*0.000*
Age 10										0.804	*0.000*	*0.000*	*0.000*
Age 11											0.185	*0.010*	*0.000*
Age 12												0.920	0.354
Age 13													0.999

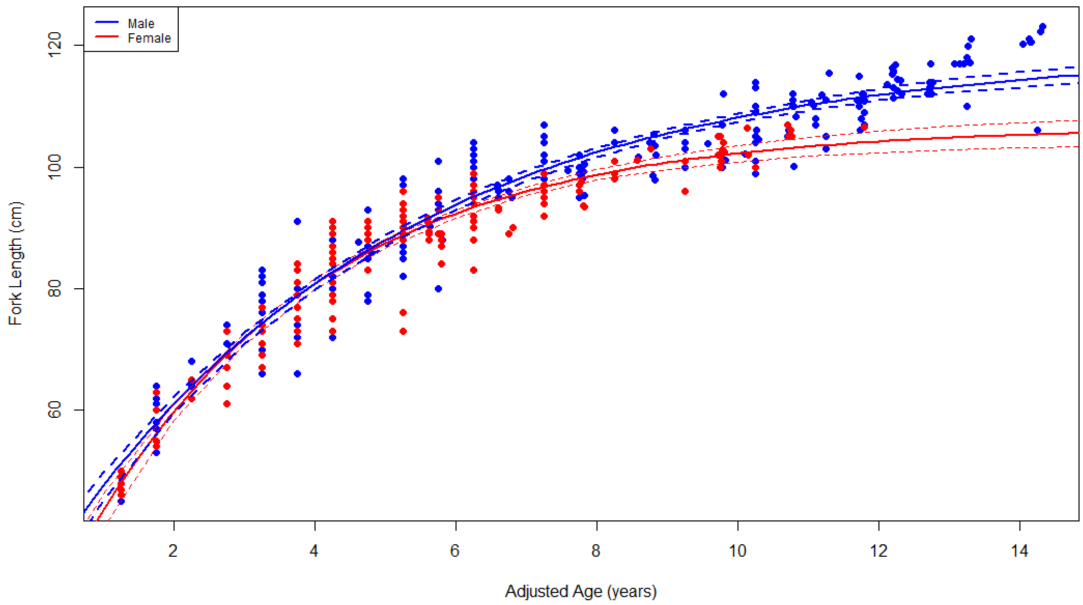

Figure 1. Sex-specific von Bertalanffy growth curves for male and female albacore. Dotted lines indicate 95% confidence intervals around the model.

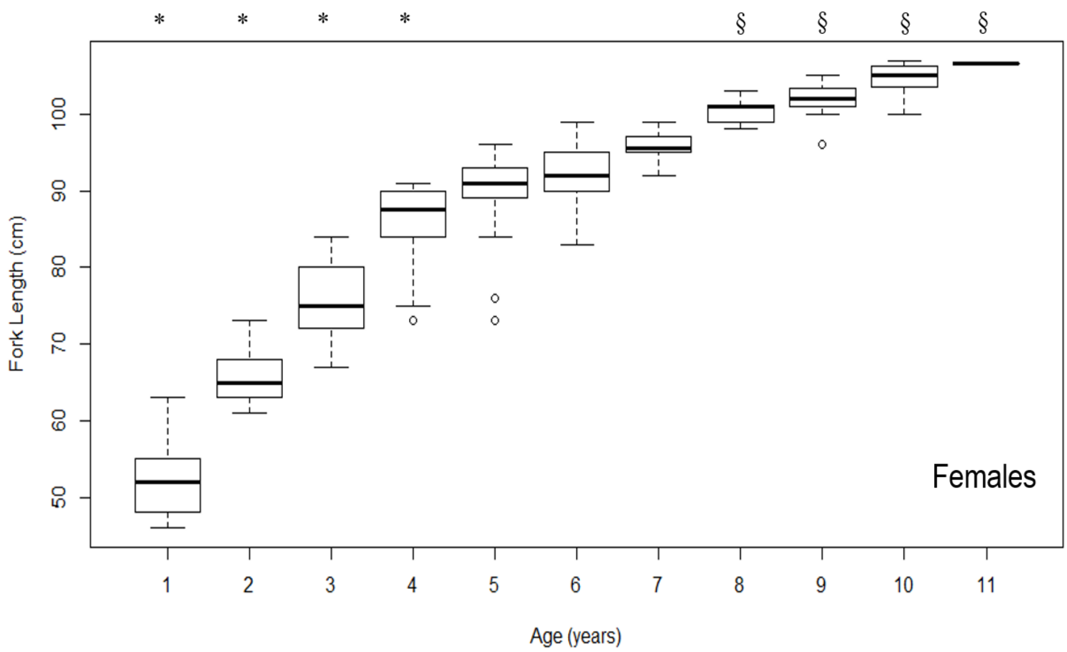

Figure 2. Boxplot of female mean length-at-age across all regions. * indicates significant different ($p < 0.05$) from all other age classes. § indicates no significant difference among marked age classes. Other age classes are not significantly different from one or more adjacent age class.

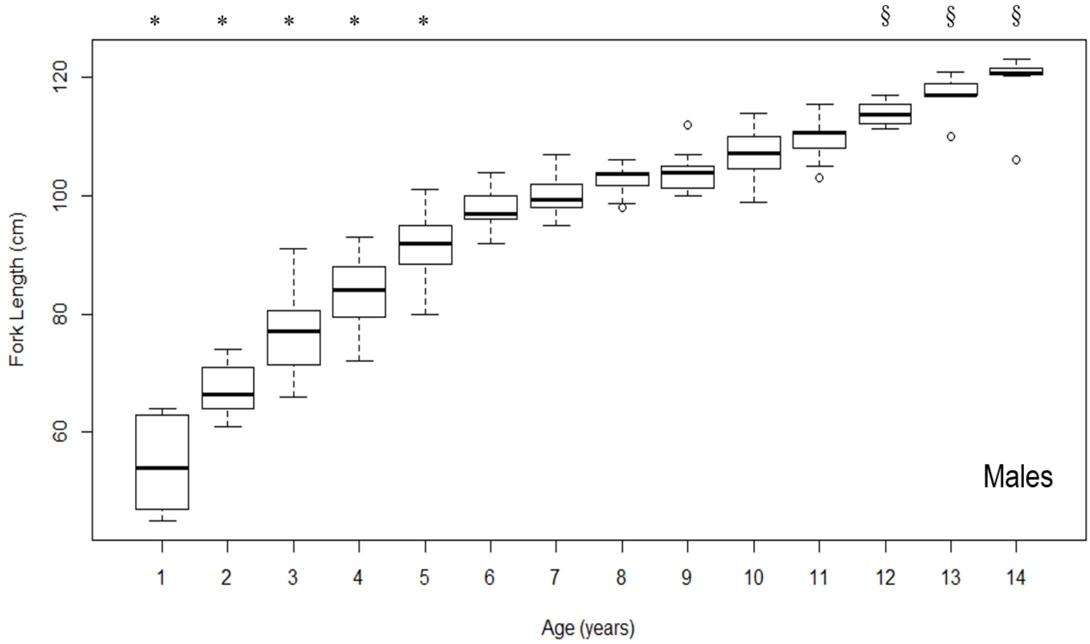

Figure 3. Boxplot of male mean length-at-age across all regions. * indicates significant difference ($p < 0.05$) from all other age classes. § indicates no significant difference among marked age classes. Other age classes are not significantly different from one or more adjacent age class.

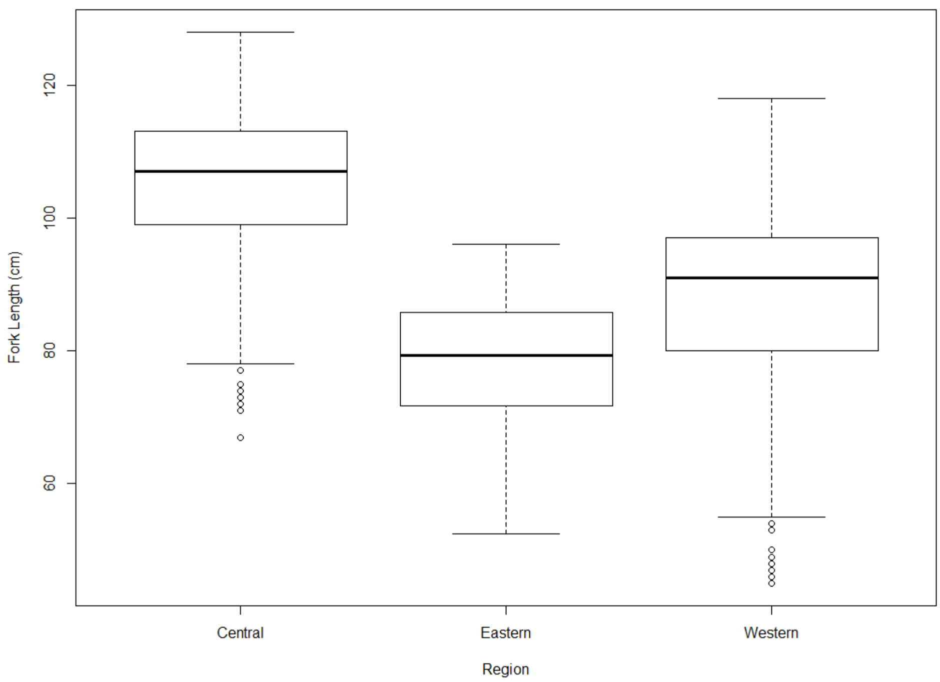

Figure 4. Boxplot of fork length (cm) by region. These data include fish of unknown sex.

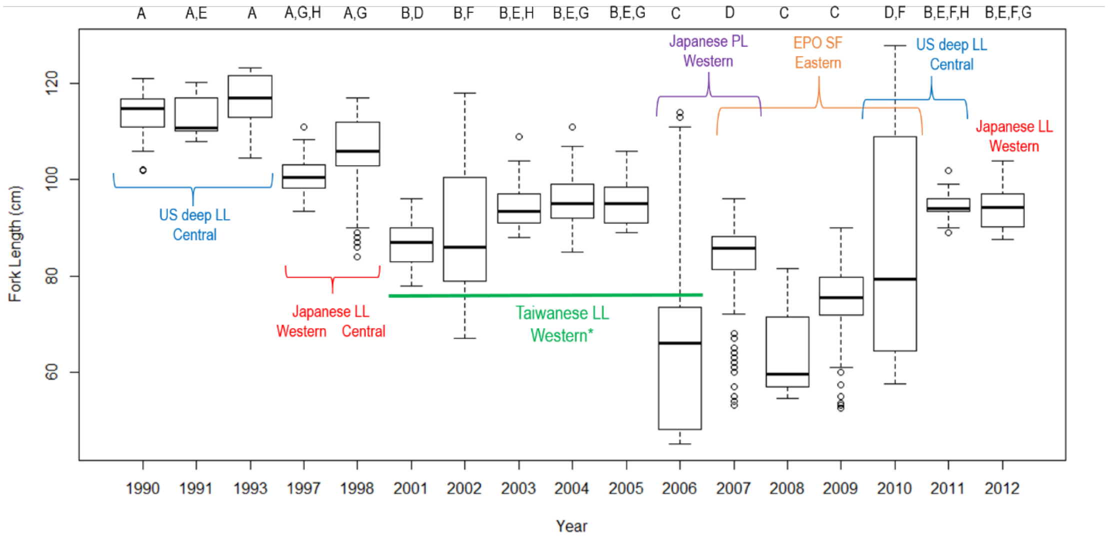

Figure 5. Boxplot of mean length by year. Fishing fleet and region is denoted for each year. LL stands for longline. PL stands for pole and line. EPO SF stands for eastern Pacific Ocean surface fishery. * denotes that in 2002 the Taiwanese collected fish from the Western and Central regions. Years that do not share a common letter (above boxplot) are significantly different. These data include fish of unknown sex.