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# Review of recent studies on the absolute and relative growth of Atlantic bluefin tuna and similarities with Pacific bluefin tuna

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## ABSTRACT

This study aims to clarify some aspects of the growth of Atlantic bluefin tuna, *Thunnus thynnus* (L.), (ABFT) mainly regarding parameters of the growth equation and of relative growth, in this case length-weight relationships. There is a great volume of literature on these matters and there is a danger that the resulting confusion may give rise to mistaken decisions.

In spite of the publication of 55 articles on absolute growth ($FL > 50$ cm), which contain a total of 43 growth equations, no consensus has yet been reached within the ABFT assessment group (AG) of the SCRS on parameters such as $L_{max}$ and $L_{\infty}$. The results of the present study indicate that the $L_{\infty}= 314.9$ cm of the growth equation used for the western stock by the AG from 2010 ($Lt= 314.9\ [1- e^{-\ 0.089\ (t\ +\ 1.13)}]$), which was discarded in 2016, lies within the confidence limits of the maximum $L$s presented in this study ($L_{max}= 321.4\pm8.7$ cm), confirming that this equation fit the biology of the ABFT growth, and does so even better than that adopted in 2016 for the western stock, whose $L_{\infty}= 271$ cm is statistically different from $L_{max}$. There is a similar situation with regard to the length-weight relationships. 38 articles ($FL > 50$ cm) have been consulted containing a total of 71 equations, but in spite of this the models adopted by the AG in 2014 underestimate the weight of spawners ($> 2$ m) by up to 23%.

The coincidence of the length-weight model for the ABFT western stock, discarded by the AG in 2014, with that of Pacific bluefin tuna, *Thunnus orientalis* (T & S), (PBFT) indicates that both species must have the same growth, something that is not surprising since both were the same species until 2003. Other coincidences, such as the trend of condition factor $K$ in adults and the growth in the first months of life, could ratify it.

In the Pacific Ocean, where far fewer growth studies have been made on PBFT than on ABFT in the Atlantic and Mediterranean, the management of growth models for the purposes of stock assessment in the International Scientific Committee (ISC) makes more sense than that carried out by the SCRS on this matter.

## KEYWORDS

*Thunnus thynnus*, *Thunnus orientalis*, growth parameters, $L_{max}$, $L_{\infty}$, length-weight relationships

# INTRODUCTION

Atlantic bluefin tuna, *Thunnus thynnus* (L.), from the Atlantic and Mediterranean, hereinafter referred to as ABFT, has suffered severe overfishing in the last decades, for this reason it is subject to a very strict regime of fishing regulation through quotas for the conservation of its resources under the supervision of the International Commission for the Conservation of Atlantic Tunas (ICCAT). The Commission has an ABFT assessment group under the Standing Committee on Research and Statistics (SCRS) which carries out periodic assessments of resources to examine the impact of such conservation measures on the population.

The age and growth of ABFT, which began to be studied almost a century ago, are of great importance for the correct evaluation of the species' resources. In this sense, since the meeting of the ABFT assessment group in 2010 (ICCAT, 2010a) two very similar growth equations have been applied to the two stocks for the first time: to the western stock, $L_t = 314.90 \, [1- e^{- 0.089 \, (t +1.13)}]$ (Restrepo et al., 2010), and to the eastern stock, $L_t = 318.85 \, [1- e^{- 0.093 \, (t + 0.97)}]$ (Cort, 1991; Cort et al., 2014). The latter has been applied in the SCRS ABFT group since 1991. This use of similar equations represented a great advance with respect to previous assessments of ABFT stocks, as up until then two very different equations had been used ($L_t = 382 \, [1- e^{- 0.707 \, (t + 0.079)}]$) (Turner and Restrepo, 1994) for the western stock, and Cort (1991) for the eastern stock. However, a year later the group Luque et al. (2011) and Landa et al. (2011) put forward alternative relationships for the eastern ABFT stock arguing that, based on reported ABFT catch lengths, the estimated $L_\infty = 382.7$ cm and $L_\infty = 348$ cm were more realistic than the currently used $L_\infty$ for this stock (318.85 cm).

In view of all this and because the ICCAT Manual (ICCAT, 2010b) and Juan-Jordá et al. (2012) provided values of $L_{max} = 426.7$ cm and $L_{max} = 372$ cm, respectively, Cort et al. (2013) carried out a study of $L_{max}$ based on a sample of around 2.5 million ABFT taken from 224 scientific publications (2,184,978 records) and available biometric data (273,050 records). Outliers had to be filtered from the latter under very reasonable scientific criteria based on Fulton's condition factor, $K$ (Ricker, 1975). The results show that the maximum fork length ($L_{max}$) observed in eastern Atlantic and Mediterranean ABFT fisheries is $319.93 \pm 11.3$ cm (CI 95%). The study concluded that the mean asymptotical length parameters, $L_\infty = 314.9$ cm (from Restrepo et al., 2010) and $L_\infty = 318.85$ cm (from Cort, 1991), lie within these confidence limits, confirming that these equations fit the biology of the growth of this species and that there is no scientific justification for changing them.

Despite this extensive work the group continued publishing articles on this subject. The results of the latter differ greatly among one another: Rodríguez-Marín et al. (2013): $L_\infty = 380$ cm; $L_\infty = 392$ cm; Luque et al. (2014): $L_\infty = 327$ cm, $L_\infty = 382$ cm; Landa et al. (2015): $L_\infty = 349$ cm; Rodríguez-Marín et al. (2016): $L_\infty = 318$ cm, $L_\infty = 324$ cm. The enormous variability of these results reveals great confusion and contradictions among these studies, especially considering the last paper presented to the SCRS by Rodríguez-Marín et al. (2017), which tends to accept $L_\infty = 260–280$ cm as the most likely for ABFT of the eastern stock. To add to the confusion even further, Murua et al. (2017) have published an article determining $L_{max} = 400$ cm.

With regard to the growth equation of the western stock, Busawon et al. (2015) presented a new reading interpretation of otoliths, in which an overestimation of the stock by otolith readings by 3 years is attributed to Restrepo et al. (2010). Based on the latter, the ABFT stock assessment group has adopted the new model of Ailloud et al. (2017), whose $L_\infty = 271$ cm.

Although Cort et al. (2015, 2016) and Cort and Estruch (2017) have published several articles on the subject, the present study discusses once more the length-weight models adopted by the SCRS in 2014

In light of the above, the specific objectives of the present study are:

i) Based on Cort et al. (2013), to estimate the value of $L_{max}$ for the population as a whole (eastern and western stocks).
ii) To review the ABFT growth equation currently (pre-2017) used for the western stock (Restrepo et al., 2010) and to compare $L_{max}$ and $L_\infty$ distributions of this equation with those recently adopted by the SCRS for that stock (Ailloud et al., 2017) under the normality hypotheses, with the aim of determining which better estimate ABFT growth.
iii) To determine the residuals when using the length-weight models adopted by the SCRS along with samples of which the actual weight is known, for which condition factor $K$ is applied.
iv) To analyze and discuss the weight underestimation of length-weight relationship models adopted by the SCRS in 2014, including recent biological information of Pacific bluefin tuna, *Thunnus orientalis* (T. & S.), (PBFT).
v) To compare the management of growth models of ABFT and PBFT carried out in scientific committees of the Atlantic and Pacific oceans.

## *MATERIAL AND METHODS*

### $L_{max}$ *analysis*

Cort et al. (2013) carried out an extensive review of scientific publications on ABFT from most known fisheries, and specifically those containing biological information referring to ABFT *Ls* in cm or *W* in kg, for the purpose of providing the maximum and minimum values of *L* and *W* of ABFT sampled. The study includes a great deal of unpublished biological information from diverse research institutions and ABFT fishing and commercial companies. The studies consulted run from old records of catches of large specimens taken in the North Sea between 1605 and 1921 (Le Gall, 1927) to recent electronic tagging studies (Block et al., 2009) and other biological samplings (Golet, 2010).

### $L_\infty$ *estimation*

Of the 55 studies on absolute growth made for ABFT (fork length > 50 cm) in the Atlantic and Mediterranean, the 32 containing growth equations were analyzed by Cort et al. (2015; 2017). In total, 43 equations were analyzed on the basis of $L_\infty$ and $L_{max}$ and

the confidence intervals shown in Cort et al. (2013). The present study only analyzes the models used in the ABFT stock assessment group. Namely:

The growth equation for the eastern Atlantic bluefin tuna stock (Cort, 1991; Cort et al., 2014) is a combined growth curve using modal progression data for ages 1 to 8 (53.5–177.2 cm) from the Bay of Biscay (Cort, 1990) and direct age-length observations (fin spine sections) for ages 9–15 (190–247 cm) from the traps of southern Spain (Rey et al., 1987; Cort, 1990). Samples used correspond to the month of June, the month of birth for the ABFT in the western Mediterranean (García et al., 2003 and 2005); this makes the sampling season equivalent in both areas. By grouping the mean values at age from the Bay of Biscay with those of the traps, the von Bertalanffy growth model could be applied. Cort et al. (2014) used the same data and tag-recovery data from tagging surveys in the Bay of Biscay, western Mediterranean and western Atlantic ($n= 131$).

Restrepo et al. (2010) used combined otolith-based age readings with the size frequency distributions of small (ages 1–3) ABFT caught by purse seiners in the 1970s; the accuracy of the age readings has been validated with bomb radiocarbon dating (Neilson and Campana, 2008). These age readings are primarily for large ABFT (ages 5 and older) and indicate slower growth and older ages than was previously assumed (Turner and Restrepo, 1994). However, an analysis of these data resulted in growth curves that predicted very small mean sizes for the youngest age group, which could be a result of the lack of small fish in the data used. The von Bertalanffy (1938) growth model was applied.

Ailloud et al. (2017) growth parameters were derived from an integrated analysis of tag-recapture data and otolith age-length. Otolith samples were prepared and read by experts following the standardized protocol outlined in Secor et al. (2014) and Busawon et al. (2015), which prescribes the use of a reference scale to identify the first annulus and multiple reads per otolith to detect any inconsistencies and reduce ageing error. Strict data quality control measures were applied to the tagging data for quality assurance and a subsample of $n= 1,118$ records were retained for use in the analysis. Two forms of the Schnute growth model were considered: the Richards model and the von Bertalanffy model.

*Determination of outliers and Fulton´s condition factor (K)*

According to Cort et al. (2013):

Grubbs (1969) defined an outlier as: "*An outlying observation, or outlier, is one that appears to deviate markedly from other members of the sample in which it occurs.*

*Outliers can occur by chance in any distribution, but they are often indicative either of measurement error or that the population has a heavy-tailed distribution. In the former case one wishes to discard them or use statistics that are robust to outliers, while in the latter case they indicate that the distribution has high kurtosis and that one should be very cautious in using tools or intuitions that assume a normal distribution*".

In order to remove outliers of *L* and *W* from various datasets available, the Fulton's condition factor *K* was calculated for each and every fish.

Fulton's condition factor (*K*) is defined as:

$$K = 10^5 * W/L^3$$

where, *W*= round weight, in kg; *L*= fork length, in cm.

According to Deguara *et al.* (2013), Tukey's outlier method (Tukey, 1977; Hoaglin et al., 1983) was then used on the values of factor *K* to detect and eliminate outliers.

After applying Tukey's methodology for outliers, the box-and-whisker plots were shown in Cort et al. (2013). The upper and lower limits of *K* indicated from this analysis are between 1.47 and 2.56.

With this methodology, common mistakes such as change of length by weight, and vice versa, or typography etc. can be eliminated from datasets. Some examples taken from Figure 1 of Cort et al. (2013) help us to understand this issue:

*L*= 382 cm; *W*= 560 kg; *K*=1.0

On the contrary:

*L*= 135 cm; *W*= 310 kg; *K*=12.6

The former might be called 'flat' tunas, and the latter, 'rounded' tunas.

The first set would include ABFT with $L_{max}$ and $W_{max}$ values of ICCAT Manual (ICCAT, 2010b):

*L*= 427 cm; *W*= 726 kg; *K*=0.93

The evolution of *K* throughout the year is studied by means of the samples used in the present work. The results have been compared with *K* values obtained using the monthly *L-W* equations of Rodríguez-Marín et al. (2015) for a fixed value of straight fork length (*SFL*)= 220 cm.

In order to verify the relationship between *K* and the residual obtained by applying different length-weight equations, various analyses on samples whose size and actual weight are known have been conducted.

### *Length-weight relationships adopted by the SCRS*

Cort et al. (2015), and Cort and Estruch (2016; 2017) conducted statistical analyses of the models recently adopted by the SCRS. In these articles two bi-variant samples (*SFL* (cm), *RW* (kg)) were used with the aim of validated them and establishing which of the models analyzed best fitted the reality represented by the samples, and would therefore have the greatest descriptive and predictive power.

The sample for the western stock (*n*= 698 ABFT) is based on data of spawners from the Gulf of Mexico (Knapp et al., 2010) and from fisheries of Canada (Caddy et al., 1976; Butler et al., 1977; Smith et al., 2006; Corrigan et al., 2007; Fraser, 2008 and database

from Fisheries and Oceans Canada). The sample contains a few young ABFT obtained from Rivas (1954), Baglin (1976); Farber and Chewning (1980); Hurley and Iles (1982), and our own data from transatlantic migrations (East to West), cited in Cort (1990).

The sample for the eastern stock (*n*= 474 ABFT) is based on samples from the Atlantic traps of Morocco (Abid et al., 2015 and INRH Database), Portugal (IPMA database, in Cort et al., 2013) and Spain (Rodríguez-Roda, 1967 and IEO database), and a number of samples from ICCAT-GBYP database selected at random, covering the lack of young ABFT.

From all the statistical analysis carried out, the present study has recovered the residual analysis of the population models (for western and eastern stocks) adopted by SCRS.

For a linear or non-linear regression model, the difference between the observed value of the dependent variable (*y*) and the predicted value (*ŷ*) is called the residual, *e*: $e = y - \hat{y}$. For an appropriate model the mean of the residuals should be close to zero and the standard deviation should not be too large. If the residuals are represented by plotting its values on the vertical axis and the independent variable on the horizontal axis (residual plot), for an appropriate model the points in the residual plot must be randomly dispersed around the horizontal axis.

### *Review of growth equations and length-weight relationships for ABFT and PBFT*

A review of growth papers (absolute and relative) is made, emphasizing those used in the stock assessment groups of SCRS and ISC (International Scientific Committee) of the Western & Central Pacific Fisheries Commission (WCPFC). An analysis is made of how these two scientific committees manage the growth models used for stock assessment of ABFT and PBFT.

### *Capture of a giant PBFT in the Pacific Ocean*

On the capture of the largest PBFT captured to date published by the Japanese press (information contrasted with Japanese scientists), a comparison of length-weight relationship of PBFT (Shimose et al., 2009) has been established with several length-weight models of ABFT (Parrack and Phares, 1979; Rodríguez-Marín et al., 2015). The purpose of this comparison is to determine which best fits the data of the largest ABFT and PBFT captured. In this sense, the data of the largest specimens recorded in the Pacific and Atlantic oceans have also been superimposed on the length-weight models.

The Japanese length-weight relationship refers to gilled and gutted weight, and so the conversion factor of ABFT of 1.16 has been applied (ICCAT, 1997).

### *Parallelism and differences of some biological parameters related to growth between ABFT and PBFT*

Until 2003 both species were considered a single species, and for this reason similarities in some parameters related to growth have been found. Based on diverse synopsis and recent articles, spawning season, *K* factor, and growth of group 0 and other groups are analyzed in the present study.

## RESULTS

### $L_{max}$ and $L_\infty$ analysis

From a sample larger than 2.4 million ABFT (Table 1), the mean $L_{max}$ was established at 321.4±8.7 cm (SD) for the Atlantic and Mediterranean (both stocks). The largest wild specimens of the eastern stock are the following: a 725 kg fish caught in the Marmara Sea in 1936 (Lebedeff, 1936), a record validated by the International Commission for the Exploration of the Mediterranean, CIEM (Heldt, 1938). Akyüz and Artüz (1957) sampled an ABFT of 330 cm caught in the Marmara Sea in 1956. Hamre et al. (1971) carried out further sampling in the market of Istanbul in 1967 and 1968 and measured ABFT of 320 cm. For the western stock, Crane (1936) mentions a 726 kg specimen landed in Portland (Maine), but refers to a news article from the press. The official record of the largest ABFT captured in the western Atlantic is 679 kg, a fish caught in Nova Scotia waters in 1979 (Fraser, 2008), the current Guinness world record. Fraser (pers. commun.) reported the fish size: *Ten feet and six inches* (sic): 320 cm. Knapp et al. (2010) cite an ABFT of 326 cm (*SFL*) −655 kg−, from the sampling carried out during the 2007 and 2008 spawning seasons in the Gulf of Mexico.

Di Natale et al. (2017) cite a 1,056 kg wild ABFT caught by a Spanish longliner in the Mediterranean in 2002 and auctioned at the Tokyo fish market the same year (Di Natale, pers. commun.). With respect to this, IEO has been monitoring all catches of Spanish longliners in the Mediterranean for more than four decades, especially swordfish (*Xiphias gladius*, L.) and ABFT (De la Serna et al., 2004), and this fish does not appear in any database.

Table 1. Results of the largest ABFT observed by geographical area and source of information.
Cort et al. (2013)

| Zone | Total ABFT Sample size | Publications consulted | Unpublished Db (ABFT sampled) | $L_{max}$ (cm) observed (wild) | Place/Source | $W_{max}$ (kg) observed (wild) | Place/Source/Observations |
|---|---|---|---|---|---|---|---|
| Eastern & Central Med | 749,257 | 55 | 15,184 | 330 | Marmara and Black seas/Akyüz & Artüz (1957) | 725 | Marmara sea/ Lebedeff (1936), Heldt (1938) |
| Western Med | 505,470 | 36 | 51,639 | 310 | Tyrrhenian sea/Arena (1981, 1982); Di Natale et al. (2003, 2005) | 685 | Sardinia trap/Sarà (1969) |
| Central/Eastern Atlantic | 561,365 | 73 | 191,837 | 319.8 | Canary islands/Santos Guerra (1976a,b;1980); ICCAT (1976) | 560 | Norwegian waters/Nøttestad, based on Hamre´s data |
| Western Atlantic | 368,886 | 60 | 14,390 | 326 | Gulf of Mexico/Knapp et al. (2010) | 679 | Canadian waters (Nova Scotia)/Fraser (2008)/Recreational fishing world record |
| TOTAL | 2,184,978 | 224 | 273,050 | | | | |

In Figures 1A and 1B the probability density functions (PDF) of $L_{max}$ (mean±SD=321.4±8.7 cm) are compared with those of $L_\infty$ by Ailloud et al. (2017) (mean±SD=271±22 cm) and Restrepo et al. (2010) (mean±SD=314.9±19.4) cm, under the normality hypothesis.
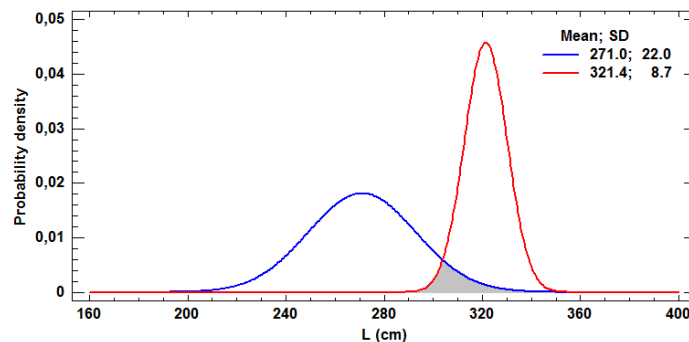


Figure 1A. Normal PDF plots. Blue line corresponds to the PDF of $L_\infty$ (271±22 cm); red line corresponds to the PDF of $L_{max}$ (321.4±8.7 cm). The shaded area is the level of coincidence between both distributions
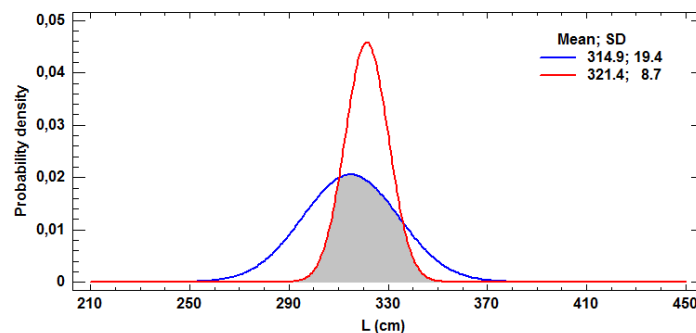


Figure 1B. Normal PDF plots. Blue line corresponds to the PDF of $L_\infty$ (314.9±19.4 cm); red line corresponds to the PDF of $L_{max}$ (321.4±8.7 cm). The shaded area is the level of coincidence between both distributions

In the first case there are two completely different distributions, with an approximate level of coincidence of only approximately 9%, indicating that the adopted model (Ailloud et al., 2017) is statistically very far from the reality. In the second case the distributions are much more similar. For both, the mean values are similar and the standard deviations do not differ excessively, and the level of coincidence is approximately 60.3%.

After analyzing 43 ABFT growth equations, Cort et al. (2014; 2017 found nine studies (from eastern and western stocks) in which the values of $L_\infty$ lie within the limits of $L_{max}$: Bard et al. (1978); Hattour (1984); Cort (1991; Cort et al., 2014); Negli and Naour (2014); Parrack and Phares (1979); Farber and Lee (1981); Restrepo et al. (2010); Luque et al. (2014), and Rodríguez-Marín et al. (2016).

## *Estimation of K*

Different *Ks* applied to $L_\infty$ of Ailloud et al. (2017) and Restrepo et al. (2010) for the highest weights observed on ABFT are presented in Table 2.

Table 2. *K* values for the highest weights, corresponding to $L_\infty$
and to the extremes of its confidence intervals,
from Restrepo et al. (2010) and Ailloud et al. (2017)

| | $L\_i$ | $L\_inf$ | $L\_s$ | $W = 600$ | | | $W = 650$ | | | $W = 725$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $K$i | $K$ | $K$s | $K$i | $K$ | $K$s | $K$i | $K$ | $K$s |
| Ailloud et al. | 227.9 | 271.0 | 314.12 | 5.1 | 3.0 | 1.9 | 5.5 | 3.3 | 2.1 | 6.1 | 3.6 | 2.3 |
| Restrepo et al. | 276.9 | 314.9 | 352.9 | 2.8 | 1.9 | 1.4 | 3.1 | 2.1 | 1.5 | 3.4 | 2.3 | 1.6 |

$L$i=Linf-1.96*SD

$L$s=Linf+1.96*SD

These results show that for Ailloud et al. (2017), the *K*-values corresponding to $L_\infty$ and $L_i$ remain outside the interval (1.47–2.56) and for Restrepo et al. (2010) only the values corresponding to $L_i$ remain outside, confirming the results of the previous exercise in which the latter is better adapted to the growth of ABFT than that adopted by the SCRS.

A compendium of works in which the actual value of the samples are estimated can be consulted in tables 10A and 10B of Cort and Estruch (2017). The evolution of *K* throughout the year obtained from these tables, and Figure 2 (summarized in Table 3) can be explained as follows: there are three periods, July-August (after reproduction), when ABFT is skinny. Immediately afterwards there is a growth period of high fattening extending from September until December. And finally, at the end of the boreal winter, when reproduction begins (March-April), the *K* index drops back to the levels of June, which is the lowest point, when ABFT is in full reproduction.
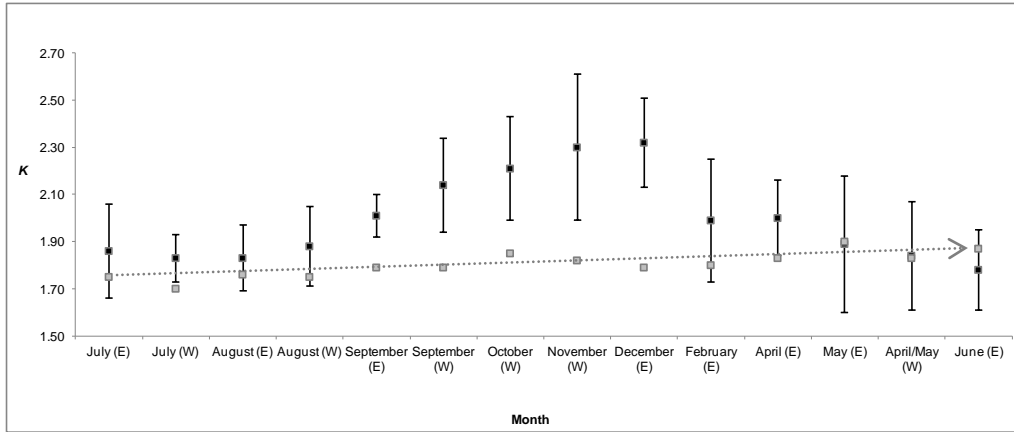
Figure 2. Evolution of *K* throughout the year

■ Mean values obtained by using data of tables 10A and 10B of Cort and Estruch (2017)
■ Values obtained by using monthly *L-W* of adopted equations (Rodríguez-Marín et al., 2015).
See data, Table 3.
·············▷ *K* trend using monthly *L-W* equations adopted by SCRS (Rodríguez-Marín et al., 2015)

In the same figure the values of *K* are presented using monthly length-weight equations adopted by SCRS (Rodríguez-Marín et al., 2015). In this case, *K* values are very low, not reaching *K*= 2 at any time. The line is flat and does not manifest the high fattening period (September-December). Values only coincide in May. In June, however, *K* is overestimated.

Table 3. Evolution of *K* throughout the year (E: East Atlantic samples. W: West Atlantic samples).
Sample size = 1,315 ABFT
■ Mean values obtained by using data from Tables 10A and 10B of Cort and Estruch (2017).
■ Values obtained by using monthly *L-W* adopted equations (Rodríguez-Marín et al., 2015).
(LL, Long line)

| | | Western and Eastern Atlantic | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | *K* ■ | Max | Min | Stand Dev. | *N* | Observations | *K*-ICCAT ■ | *W* (kg), 220 cm |
| July (E) | 1.86 | 2.06 | 1.66 | 0.20 | 127 | Traps, Hand line (S. of Gibraltar) | 1.75 | 187 |
| July (W) | 1.83 | 1.93 | 1.73 | 0.10 | 57 | Canada | 1.70 | 181 |
| August (E) | 1.83 | 1.97 | 1.69 | 0.14 | 144 | Traps (S. of Gibraltar) | 1.76 | 187 |
| August (W) | 1.88 | 2.05 | 1.71 | 0.17 | 135 | Canada | 1.75 | 187 |
| September (E) | 2.01 | 2.10 | 1.92 | 0.09 | 16 | North Sea (Spor) | 1.79 | 191 |
| September (W) | 2.14 | 2.34 | 1.94 | 0.20 | 153 | Canada | 1.79 | 190 |
| October (W) | 2.21 | 2.43 | 1.99 | 0.22 | 122 | Canada | 1.85 | 197 |
| November (W) | 2.30 | 2.61 | 1.99 | 0.31 | 29 | Canada | 1.82 | 194 |
| December (E) | 2.32 | 2.51 | 2.13 | 0.19 | 51 | Morocco (Hand line) | 1.79 | 191 |
| February (E) | 1.99 | 2.25 | 1.73 | 0.26 | 39 | Traps (S. of Gibraltar) | 1.80 | 191 |
| April (E) | 2.00 | 2.16 | 1.84 | 0.16 | 91 | Traps (S. of Gibraltar) | 1.83 | 195 |
| May (E) | 1.89 | 2.18 | 1.60 | 0.29 | 211 | Traps (S. of Gibraltar) | 1.90 | 201 |
| April/May (W) | 1.84 | 2.07 | 1.61 | 0.23 | 25 | Gulf of Mexico (LL) | 1.83 | 196 |
| June (E) | 1.78 | 1.95 | 1.61 | 0.17 | 115 | Traps (S.of Gibraltar) | 1.87 | 199 |

The above issue can be corroborated as follows: Figure 3 shows the relationship between the value of *K* for each sample from Tables10A and 10B of Cort and Estruch (2017), and the residuals obtained for each applying the monthly length-weight equations adopted by SCRS (Rodríguez-Marín et al., 2015).

The results clearly show how the residuals increase as *K* also increases. The residual from *K* can be predicted by the regression line. When fish are in the low fattening condition the residual value is low (< 5%), while for fish in the high fattening condition the residuals can reach 23%.
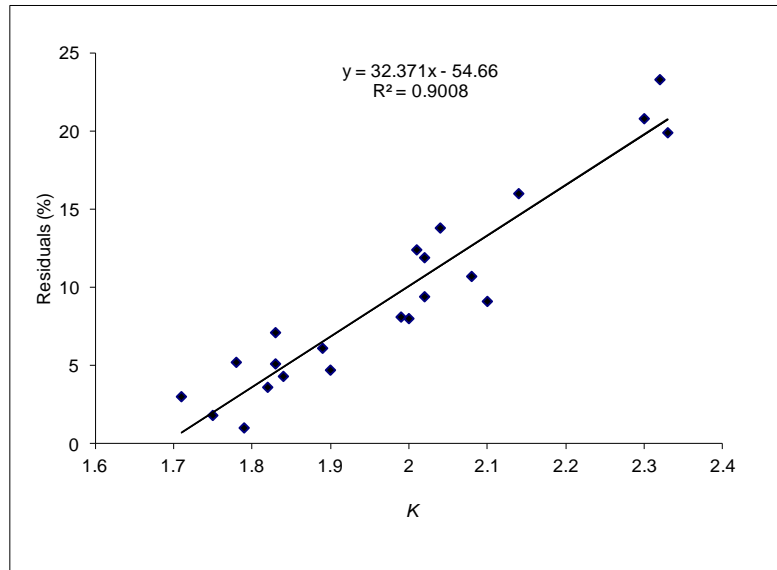


Figure 3. Relationship between *K* and residuals
obtained by applying monthly length-weight models adopted by SCRS

### *Length-weight relationships adopted by the SCRS*

Based on a statistical analysis, Cort et al. (2015) and Cort and Estruch (2016; 2017) demonstrated that the length-weight relationships adopted by SCRS in 2014 (ICCAT, 2014a,b), referred to as *West* and *East* in the present study, underestimate the weight of spawning ABFT (> 2 m) by up to 14%.

From the results of the analysis of the residuals (Table 4) it is observed that the mean and median values point to an important asymmetry of the residuals for the models *West* and *East*, which can be confirmed visually in Figures 4A, 4B. The positive values of the mean (as well as the confidence intervals) for *West* and *East* confirm the tendency of these models to underestimate weight. Besides, the requisite that the 95% confidence interval for the mean of the residuals contains the value 0 is not fulfilled.

Table 4. Summary statistics for the residuals corresponding to the different
models analyzed and confidence intervals (95%) for the mean

|  | *West* | *East* |
|---|---|---|
| Count | 698 | 474 |
| Mean | 35.4744 | 11.7863 |
| Standard deviation | 37.1325 | 19.7551 |
| Median | 28.619 | 0.4584 |
| 95% confidence interval for the mean | 35.4744 +/- 2.7547 [32.7197; 38.2291] | 11.7863 +/- 1.783 [10.0033; 13.5693] |
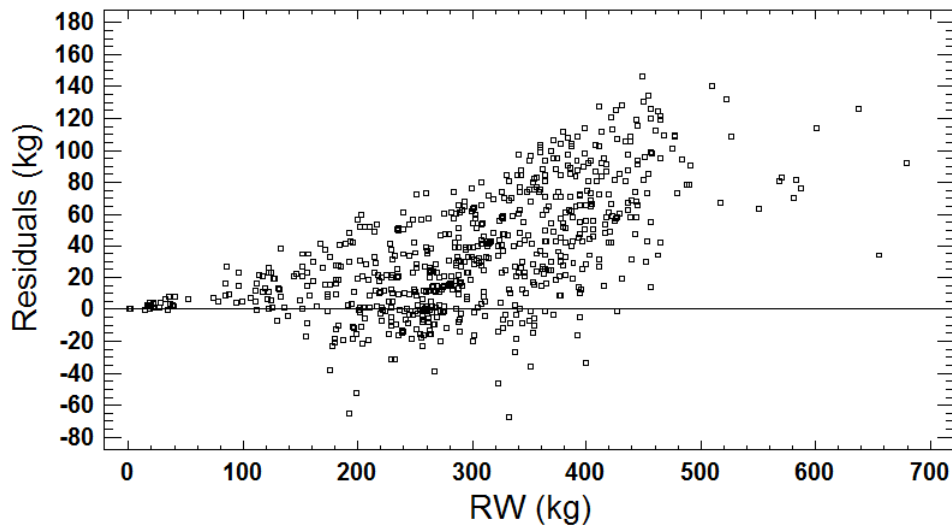
Figure 4A. Residual plot. The figure corresponds to the model linked to
the equation adopted for the western stock (*West*)
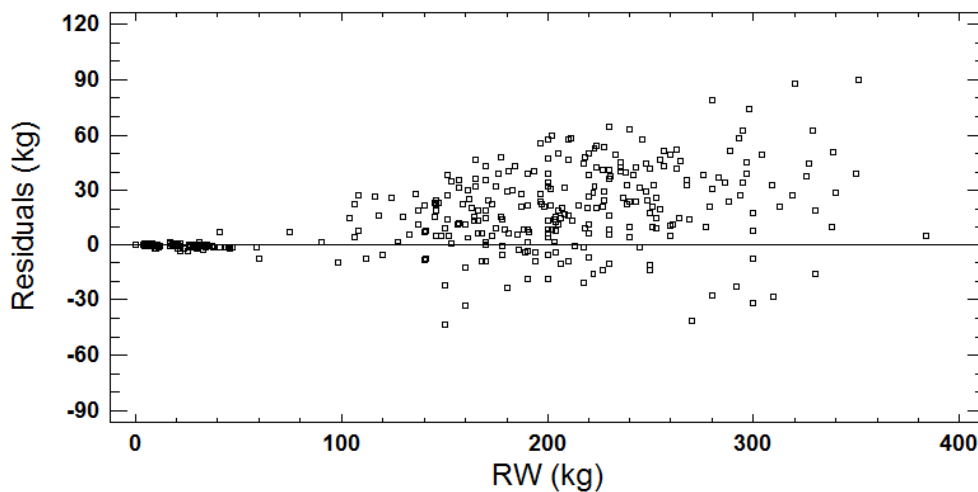


Figure 4B. Residual plot. The figure corresponds to the model linked to
the equation adopted for the eastern stock (*East*)

In view of all this, it can be concluded that adopted models *West* and *East* are not
suitable for explaining the behaviour of the sample data.

### Review of growth equations and length-weight relationships for ABFT and PBFT

In the latest reviews, Rooker et al. (2007), Cort et al. (2013; 2014) and Murua et al.
(2017), 55 articles (*FL* > 50 cm) on the absolute growth of wild ABFT are reported. Of
these, 32 contain 43 growth equations. In relation to length-weight relationships, Cort et
al. (2013) report 37 articles with 57 equations. Rodríguez-Marín et al. (2015) publish 12
monthly and 2 population equations (western and eastern stocks).

The situation for PBFT is completely different since a total of 12 articles have been found: Aikawa and Kato (1938); Yukinawa and Yabuta (1967); Bayliff et al. (1991; 1993); Foreman (1996); Tanaka et al. (2007); Shimose et al. (2009); and Shiao et al. (2017), refer to absolute growth. Two deal with daily increments in otoliths at age 0: Itoh (2009), and Yamasaki et al. (2010). Shimose and Ishihara (2015) is a manual; and Tanabe and Kai (2007); and Shimose et al. (2009), deal with length-weight relationships.

## *ABFT*

### *Growth equations*

Parameters of Richards model for growth in Ailloud (2017) used for western stock (stock assessment, 2017):

$$L_t = \left(33^{-0.12} + (270.6^{-0.12} - 33^{-0.12}) \cdot \frac{1 - e^{-0.22 \cdot t}}{1 - e^{-7.48}}\right)^{-\frac{1}{0.12}}$$

$L_\infty = 271$ cm

This model replaces the previous one used for 2010 and 2014 stock assessements (Restrepo et al., 2010):

$L_t = 314.90 \, (1- e^{-0.089 \, (t+1.13)})$

Current equation for ABFT (eastern stock) from Cort (1991); Cort et al. (2014):

$L_t = 318.85 \, (1- e^{-0.093 \, (t+0.97)})$

### *Length-weight relationships*

The models traditionally used for stock assessment, both eliminated in 2014, were:

Parrack and Phares (1979), western stock:

$RW = 0.0000152 \, SFL^{3.0531}$

Arena (unpublished), in ICCAT (2006), eastern stock:

$RW = 0.000019607 \, SFL^{3.0092}$

Models adopted in 2014, Rodríguez-Marín et al. (2015):

Western stock: $RW = 0.0000159137 \, SFL^{3.020584}$

Eastern stock: $RW = 0.0000315551 \, SFL^{2.898454}$

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*PBFT*

*Growth equations*

Current equation for PBFT (Shimose et al., 2009):

$L_t$= 249.6 (1- e$^{- 0.173 (t + 0.254)}$), slightly modified for 2016 stock assessement by Anonymous (2016):

$L_t$= 249.9 (1- e$^{- 0.188 (t + 0.422)}$)

*Length-weight relationships*

The relationship between fork length (*SFL*, cm) and gilled and gutted body weight (*BW*, kg), published by Shimose et al. (2009) is:

*BW*= 3.32 10$^{-5}$ *SFL*$^{2.89}$; slightly modified for 2014 stock assessment (Anonymous, 2014) by Kai (2007):

*RW*= 0.000017117 *SFL*$^{3.0382}$

In both cases (growth curves and length-weight relationships) the new models adopted for the stock assessment in the Pacific are practically the same as the previous ones, while the opposite is true in the Atlantic.

### *Capture of a giant PBFT in the Pacific Ocean*

On 06th March, 2017 the following news was published:
(http://www.tokyoreporter.com/2017/03/06/monster-tuna-caught-off-wakayama/)

*"Weighing 446 kilograms and measuring 2.82 meters in length, the "king" kuro maguro, or northern bluefin tuna was pulled aboard a longline fishing vessel about 320 kilometers off the coast on Friday. The tuna is the largest by weight since statistics started being kept by a fishery cooperative in 1949. The previous record was a 417-kilogram tuna landed in January of last year."*

The captured giant had a *L*= 282 cm and *W*= 446 kg which, according to Japanese scientists consulted, would be gilled-and-gutted weight, so the actual weight was 517 kg (converted to round weight).

Table 5 and Figure 5 show two length-weight relationships for ABFT and PBFT (converted to round weight). Parrack and Phares (1979) model was discarded by the ABFT evaluation group in 2014 and Rodríguez-Marín et al. (2015) was the adopted model.

Table 5. Length-weight models by different authors
(Associated to Figure 5)

| | Shimose et al. (2009) | Parrack & Phares (1979) | R.-Marín et al. (2015) |
|---|---|---|---|
| a | 3.3E-05 | 1.5E-05 | 1.77E-05 |
| b | 2.89 | 3.0531 | 3.0013 |
| $FL$ (cm) | Pacific (kg) | West Atlantic (kg) | West Atlantic (kg) |
| 50 | 3 | 2 | 2 |
| 70 | 8 | 7 | 6 |
| 90 | 17 | 14 | 13 |
| 110 | 31 | 26 | 24 |
| 130 | 50 | 43 | 39 |
| 150 | 75 | 67 | 60 |
| 170 | 108 | 98 | 88 |
| 190 | 148 | 138 | 122 |
| 210 | 198 | 187 | 165 |
| 230 | 258 | 247 | 217 |
| 250 | 328 | 318 | 279 |
| 270 | 409 | 403 | 351 |
| 290 | 503 | 501 | 435 |
| 300 | 555 | 556 | 481 |
| 305 | 582 | 584 | 506 |
| 310 | | 614 | 531 |
| 320 | | 677 | 584 |

Data from the three largest recorded specimens have been superimposed on Figure 5:

- The giant PBFT caught off Wakayama on 03/03/2017: *FL*= 282; *RW*= 517 kg.
- The PBFT exhibited at Seikai National Fisheries Research Institute, Nagasaki-shi (Japan): *FL*= 302; *RW*= 572 kg (Figure 6) [1].
- The ABFT, Guinness World Record: *FL*= 320; *RW*= 679 kg (Fraser, 2008).

[1] A fish of wild origin kept in captivity for several years.
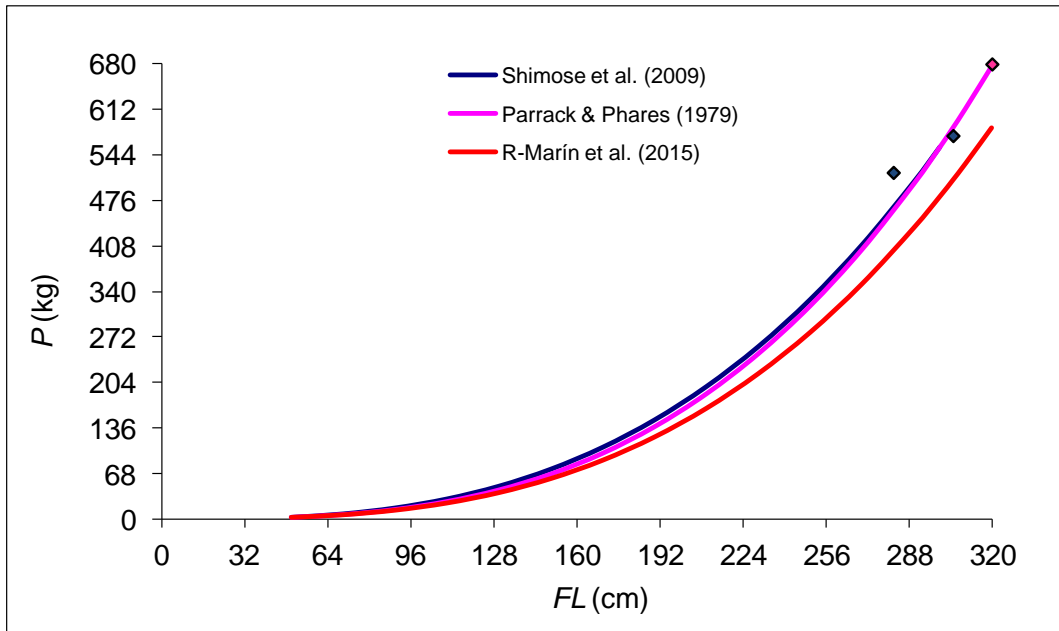
Figure 5. Length-weight models by different authors, associated to Table 6.
Explanation of three points, in text.

Figure 6. Photograph of a PBFT model (size 1:1)
exhibited at Seikai National Fisheries Research Institute,
Nagasaki-shi (Japan)

Surprisingly, the length-weight relationship of PBFT follows the same trend line of the ABFT length-weight relationship of western stock of Parrack & Phares (1979), a model that perfectly fits the growth model of Restrepo et al. (2010). The coincidence is so pronounced that they are scarcely distinguishable in Figure 5. In contrast, the equation currently in use in the SCRS differs greatly from the other two. Parrack and Phares

(1979) and Shimose et al. (2009) produce values of length and weight which are in accordance with the extreme but real superimposed specimens.

## *Parallelism and differences of some biological parameters related to growth between ABFT and PBFT*

In West Atlantic there are two spawning areas, one located in the Gulf of Mexico (Mather et al., 1995; Rooker et al., 2007; ICCAT, 2010b) and another in the Slope Sea (Northwest Atlantic), according to Richardson et al. (2016). The reproduction period extends from May to early June (Gulf of Mexico) and between June and August (Slope Sea). In western and central Mediterranean Sea the reproduction period extends from June to early July (Tiews, 1963; Corriero et al., 2005; García et al., 2005) and from May to early June (in the Levantine Sea), according to Karakulak et al. (2004).

In the synopses of Yamanaka et al. (1963) and Bayliff (1994) it´s mentioned that spawning of PBFT occurs between Japan and the Philippines in April, May, and June and off southern Honshu in July. Even in August larvae have been found in the Sea of Japan (Okiyama, 1974, 1979). According to Chen et al. (2006) spawning activity is believed to occur only in the western North Pacific Ocean especially from waters around the Ryukyu Islands to the Sea of Japan from June to August.

In general, it can be considered that ABFT and PBFT have very similar reproduction periods and sizes of the fish according to the spawning area or in captivity. The result can be verified in the following:

- As shown in Richardson et al. (2016), ABFT that reproduce in the Gulf of Mexico (20–25° N) are larger/older than those of the Slope Sea (40–45° N). In the first case, the modal value is between 15 and 17 years old; in the second, between 8 and 10. Something similar happens in the Pacific, where the PBFT spawning in the southern area (20–25° N) are larger/older (190–260 cm; from Chen et al., 2006; Shiao et al., 2017) than those spawning in the Sea of Japan, (40–45° N), 100–223 cm. The latter have been obtained from the sampling done by Shimose et al. (2009) in the fishing ports from the Sea of Japan during the spawning season.

- Both species reproduce at three years old in wild (Nakamura, 1943; cited by Hirota et al. 1976; Rodríguez-Roda, 1969) or aquaculture (Sawada et al., 2007; Berkovich et al. 2013).

-The trend of *K* factor in adults between April and July is the same for the two species, as shown by Chen et al. (2006) and the present study.

-There is a very large coincidence in the growth of group 0. Sawada et al. (2007) give 27.0±1.9 cm total length (*TL*), 248.7±80.6 g body weight (*BW*) for specimens caught for aquaculture off the coast of Kii Peninsula, Central Honshu, Japan, from August 13–20, 1997. Converting *TL* into *FL*, according to Cort (2009), the average size of the fish would be 23 cm (*FL*). La Mesa et al. (2005) caught juvenile (class 0) ABFT off the northern coast of Sicily between late August–November 2002 giving a *FL*= 22±3 cm for month II (August). The weight of these fish would range from 102 g to 258 g, according to the size-weight relationship presented by these authors.

The previous coincidences do not occur with the growth models used for ABFT (Ailloud et al., 2017; Cort et al., 2014) and PBFT (Shimose et al., 2009; Anonymous, 2016). The three models show differences for ages up to 10 years and from that age the trend towards $L_\infty$ also differs. Differences possibly due to the different methodologies used, as well as to the sampling variability.

## *DISCUSSION*

Since the beginning of the 20th century 55 studies (*FL* > 50 cm) of absolute growth of ABFT have been carried out using various methodologies, such as the reading of rings in scales, vertebrae, spines and otoliths, modal progression, tag-recaptures, back-calculated *L*, age length key, various mixed methods and others not specified. From these, 43 growth equations have been estimated in which the age of the fish is related, generally in years, together with length (Cort et al., 2014).

The ABFT $L_{max}$ controversy dates back to the 1950s when Bigelow and Schroeder (1953), revision 1.1 (2002), referring to the ABFT, state: "This is the largest Gulf of Maine fish, except for some sharks; a length of 14 feet or more, and a weight of 1,600 pounds being rumored, with fish of 1,000 pounds not rare" (14 ft= 426.7 cm, 1,600 lbs= 726 kg). Meanwhile, according to the ICCAT Manual (Chapter 2.1.5), ICCAT (2010b): "Its maximum length can exceed 4 m long. Its official maximum weight is 726 kg, but weights up to 900 kg have been reported in various fisheries of the West Atlantic and Mediterranean Sea (Mather et al. 1995)". Cort et al. (2013) have shown that 4 m $L_{max}$ is not possible: "If it is indeed just a rumor, then some comments can be made in this respect. An *L* of 426.7 cm is technically impossible. For an ABFT to reach such a size it would have to weigh 1,480 kg according to the general *L-W* relationship of the western Atlantic of Parrack and Phares (1979). Moreover, the value of *K*= 0.94 is far from the minimum size established for this species (Deguara et al., 2012)[1]. To date there is no scientific evidence whatsoever of the existence of ABFT of anything like this *W*; however, the *W* of a 726-kg bluefin tuna would vary between 312 cm and 327 cm when applying the *L-W* relationships of September-November of these authors, a value which makes more biological sense and fits in with $L_{max}$ as determined in this study."

[1] This reference has become Deguara et al. (2013)

Murua et al. (2017) state: "Atlantic bluefin tuna attain the largest body size of any tuna species, reaching a length of more than four meters (Bigelow and Schroeder 1953) and a bodymass of nearly 700 kg (Fromentin and Powers 2005)". In other words, these authors give more credence to a rumour from 64 years ago than to a published scientific article in which it is demonstrated that 4 m is impossible, according to Cort et al. (2013). In addition, these authors ignore the official reference on weight made by Lebedeff (1936) and Heldt (1938). The fact that reference is still made to a maximum length of 4 m confuses the public and makes the results and conclusions of the study on this subject incorrect.

Cort et al. (2013) suggested that the following phrase from the ICCAT Manual refers to the maximum weight: "Its official maximum weight is 726 kg, but weights up to 900 kg have been reported in various fisheries of the West Atlantic and Mediterranean Sea

(Mather et al. 1995)", be changed to: "Its official maximum weight is 725 kg (Lebedeff, 1936; Heldt, 1938)".

In relation to the capture of a wild ABFT of 1,056 kg by a Spanish longliner in the Mediterranean Sea in 2002 cited by Di Natale et al. (2017), doubts remain since it does not appear in any official Spanish registers (IEO's and ports specialized in ABFT fishing with LL), nor in the press. Moreover, if a fact of such transcendence had taken place, it would have been published at that time by the press all over the world. In the same article, however, several ABFT of 780 kg from fattening farms are cited. According to Gordoa (2010), ABFT >260 kg undergoes fattening of around 22% of its weight over a period of 3–5 months, and so these specimens would have entered the farm with about 640 kg.

In the review of the bibliography and available biometric data outliers had to be filtered out since the ABFT databases have numerous errors that can be attributed to typographical errors or to confusing weights and sizes, among others. The outliers are of great importance in obtaining a model by least square methods because their inclusion or not in the sample can greatly influence the fitting parameters.

Although the outliers recognized may be possible, the relationship between the variables defined by the fitted model can be greatly affected by the outliers, which may introduce important bias in the model that would disappear if the data that should be treated as exceptions were eliminated from the data set.

In conclusion, if our goal is to fit a model that represents the usual behaviour of the relationship between length and weight, singular data may introduce undesirable bias in the final model predictions. If we do not consider the possible but unusual data for constructing the model, the model will represent the usual behaviour and the initial outliers will continue to be outliers in reference to the values predicted by the model.
The growth equations available in the literature for this species were analyzed to determine which provided the best representation of the known biology of ABFT. Eleven growth equations of 43 have a value of $L_\infty$ within the limits of $L_{max}$ (Cort et al., 2014). This updated review demonstrates the availability of a large body of literature on age estimation and absolute growth of ABFT. With the analysis carried out, it is clearly possible to identify and conclude which are the equations that best fit the growth biology of this species, thereby ensuring the most accurate stock assessments can be carried out.

Assuming that $L_{max}$ and $L_\infty$ must have similar values (do not forget that since 1957 $L_{max}$ remains at 330 cm), the results of the present study indicate that the $L_\infty$= 314.9 cm of the growth equation used from 2010 by the SCRS ABFT assessment group for the western stock ($Lt$= 314.9 [1- $e^{-0.089 (t + 1.13)}$]) discarded in 2016, lies within the confidence limits of the maximum $L$s presented in the study: $L_{max}$= 321.4±8.7 cm. These conclusions are also valid for the equation for the eastern stock ($Lt$= 318.85 [1- $e^{-0.093 (t + 0.97)}$]). The results confirm that these two equations fit the biology of the growth of the ABFT, even better than that adopted for the western stock (Ailloud et al., 2017), which has an $L_\infty$= 271 cm, statistically different from $L_{max}$. The adopted model is based on a new interpretation of age from otoliths (Busawon et al., 2015) that strangely flattens in older ages and which questions the interpretation made by previous scientists (Restrepo et al., 2010). While von Bertalanffy's (1938) model does not fit the latter records on age,

Richards' (1959) model does. Whatever the case, this new approach, which is supported by Rodríguez-Marín et al. (2017), acknowledges the filtering done by Cort et al. (2013) to be correct, but it is in complete contradiction with the $L_{max}$= 400 cm of Murua et al. (2017).

Fulton's condition factor applied to the ABFT has been used by scientists throughout history and has provided optimal results. Rodríguez-Roda (1964) determined this index to compare the different states of fattening of ABFT during its migrations towards the spawning areas in the Mediterranean Sea and their return to the Atlantic Ocean (in 1956 and 1958). Tiews (1978) applied it to study fish consumption by ABFT during their stay in the North Sea (from 1951-1972). Deguara et al. (2013) proposed this method to filter out outliers and to provide more meaningful *L-W* relationships. In the present study the latter method has been followed taking into account that most of the guidelines provided by Froese (2006) are followed.

According to Rodríguez-Roda (1964); Santos et al. (2004); Aguado and García (2005); Chapman et al. (2011), values of *K* between 1.4 and 1.7 are values for wild ABFT in low fattening condition, far from those of spawning ABFT ($K \geq 2$), as has been demonstrated by Rodríguez-Roda (1964); Percin and Akyol (2009; 2010); Golet and Lutcavage, unpublished data cited by Chapman et al. (2011); Deguara et al. (2012), Gordoa (2010) and Galaz (2012). Changes in mean condition factor of female bluefin tuna from the south-western North Pacific by trimester periods shown by Chen et al. (2007), also show a fall during the spawning period.

The *K* index turns out to be a fundamental tool for determining the validity of ABFT growth models. Nevertheless, in our last studies we have established limits of between 1.4 and 2.6, which is a very broad range. Any value outside that range can be considered very unlikely from a statistical point of view. As an example, ABFT captured in the traps of the Strait of Gibraltar in the boreal spring while entering the Mediterranean Sea for spawning has a $K \geq 1.8$–2. The index for these fish will fall to $K$= 1.7 at the end of the spawning season in late June.

The evolution of *K* throughout the year confirms what has been said in the preceding paragraphs, namely that the length-weight equations adopted by SCRS (Rodríguez-Marín et al., 2015) underestimate the real weight of ABFT during the fattest months (September-December), while the equation for June overestimates weight. This latter fact had an immediate effect on the part of the farming sector, since the equation was applied to convert straight fork length, (*SFL*) measured with stereocameras during the caging of ABFT, to weight at catch (*RWT*). A review of published *L-W* relationships and an analysis of some new data was carried out by Deguara et al. (2017) with the final objective of providing an *L-W* equation to be used to convert to *RWT* the ABFT *SFL* data for fishes caught during the purse seine fishing season and transferred to cages. A new equation applicable to the Mediterranean Sea during the months of May and June was determined: $RWT = 2.8684 \ 10^{-5} \ SFL^{2.9076}$ (Deguara et al., 2017). The latter was adopted by SCRS and ICCAT in 2016, and began to be implemented in stereocameras in 2017.

The analysis of the residuals presented, in which the mean and the median values point to an important asymmetry of the residuals for both models, represents another proof of

the underestimation of weight of the length-weight models adopted by the SCRS for eastern and western stock since 2014.

There is a large difference in the total number of growth studies carried out on ABFT and PBFT species. In the case of ABFT, the bibliography began in 1923 (Corson, 1923) and has continued in numerous and different locations: the eastern and western Atlantic, and the Mediterranean. As far as PBFT is concerned the first paper was published by Aikawa and Kato (1938), and most of them are from the western Pacific.

The review carried out in this study shows that the management of growth for the stock assessment is performed better by ISC (WCPFC) than SCRS. It is clear that over time the knowledge of growth has improved and the new models adopted must show improvements. In the Pacific, the new growth models adopted have improved the quality of the data without simply changing the previous equations. In SCRS the opposite has happened.

The coincidence of the length-weight model for the ABFT western stock (Parrack and Phares, 1979) with that of PBFT indicates that both species must have the same growth, something that is not surprising since both were the same species until 2003. Other coincidences, such as the trend of condition factor $K$ in adults and the growth in the first months of life, could ratify it. The differences between the growth curves of both species may be due to the different methodologies used and to the lack of larger specimens, mainly in the case of PBFT. In any case, it' is always easier to obtain pairs of length-weight values than to carry out a growth study using hard parts that are not always obtainable. This happened in the case of the world record of Fraser (2008) in the Atlantic and that of the giant captured in Wakayama in 2017.

The aforementioned coincidence leads us to think that the world record for PBFT (currently 517 kg) will continue to increase over the years. With regard to ABFT, it appears that the official $W_{max}$ of 725 kg, in force since 1938, can hardly be surpassed.

The length-weight relationship model discarded by the SCRS (Parrack and Phares, 1979) fits much better (for ABFT >160 cm) than that adopted by this committee (Rodríguez-Marín et al., 2015), a model that should never provide weight values below those of PBFT.


*EPILOGUE*

In the assessment of ABFT resources analytical models are used that require the best possible demographic distribution of catches. It is therefore important to use very precise and suitable growth equations.

The ABFT assessment group of the SCRS remains unclear as to the growth parameters of this species. Therefore, the ICCAT Manual (ICCAT, 2010b) refers to $L_{max}$ in the following terms: "Its maximum length can exceed 4 m long", and the latest reports of the SCRS (ICCAT, 2015; 2016) state: "Bluefin tuna is a long-lived species, with a lifespan of about 40 years, as indicated by radiocarbon deposition and can reach 330 cm (*SFL*) and weight up to 725 kg." The difference between the two statements is abysmal. The result of the confusion on this matter is that in recent years the group has adopted

absolute (growth curve) and relative growth equations (length-weight relationships) that fail to fit either of these two values while, nevertheless, ruling out models that fitted better to the biology of the growth of the species, specifically the values cited in the latest reports of the SCRS (330 cm, *SFL*; 725 kg, *RW*).

In addition to recent publications and articles submitted to the SCRS, in the present study we have shown that the absolute growth model adopted in 2016 deviates significantly, from a statistical point of view, from the permissible values of $L_{max}$, and that the length-weight relationships adopted in 2014 significantly underestimate the weight of adult specimens.

In the Pacific Ocean, where far fewer growth studies have been made on PBFT than on ABFT in the Atlantic and Mediterranean, the management of growth models for the purposes of stock assessment in the ISC makes more sense than that carried out by the SCRS on this matter. The new models adopted by the former committee improve over the years without obfuscating the reality of the species, in stark contrast to the case of the SCRS.

The fact that models are used that underestimate ABFT size will, one way or another, affect the final results of the population analysis as well as the assessment the SCRS communicates to the Commission (ICCAT).

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