Fisheries Research 170 (2015) 190–198

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Growth of bluefin tuna (*Thunnus thynnus*) in the North-eastern Atlantic and Mediterranean based on back-calculation of dorsal fin spine annuli

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ARTICLE INFO

Article history:
Received 14 May 2014
Received in revised form 30 January 2015
Accepted 4 June 2015
Handled by B. Morales-Nin
Available online 26 June 2015

Keywords:
Bluefin tuna
Thunnus thynnus
Growth
Back-calculation
East Atlantic
Mediterranean

ABSTRACT

The growth of bluefin tuna (*Thunnus thynnus*) in the North-eastern Atlantic and Mediterranean was analysed using the back-calculation of the dorsal fin spine annuli. Spines from a total of 2678 bluefin tuna, collected from 1984 and 1990–2010, were analyzed. The specimens ranged from 45 to 287 cm straight fork length (SFL). Both linear and power regression functions showed a significant relationship between spine radius and SFL, but power function fitted better than linear ($SFL = 42.978R^{0.884}$, $r^2 = 0.98$), as also was found in previous studies when a wide range of sizes was available. Two back-calculation equations were used to obtain the back-calculated SFL, Fraser-Lee and Body Proportional Hypothesis (BPH), showing similar results. The Von Bertalanffy growth parameters obtained with the selected BPH model were: $SFL = 349.5(1 - e^{-0.086(t+0.814)})$. Back-calculated lengths and growth parameters showed similarities with those from previous literature.

1. Introduction

Growth is a critical parameter for describing the life history of fish and it is fundamental for population modeling, stock assessment and managing of exploited species (Gulland, 1988). In Tunas, as in other fish species, life history traits are consistently related and present diverse strategies given their wide ranging geographic extent in their distributions and migrations, and their adaptations to the pelagic environment (Fromentin and Fonteneau, 2001; Juan-Jordá et al., 2012). Fromentin and Fonteneau (2001) distinguish two groups of tuna species: tropical tunas which show a rapid turnover and are characterized by rapid growth, small to medium size, early age-at-maturity, long spawning duration and short life span; and temperate species which display the opposite set of traits. The three species of bluefin tuna (*Thunnus thynnus*, *Thunnus orientalis* and *Thunnus maccoyii*) belong to this last group and their features make them more fragile to exploitation. Atlantic bluefin tuna (ABFT), *T. thynnus* (Linnaeus, 1758), is a species of great commercial interest, which has been in an overfished condition because of its high demand in the Japanese market and the difficulty of its management due to the high number of countries involved in its capture, resulting in a fishing overcapacity. At present this species is subject to a multiannual recovery plan. The stock assessments for ABFT use age-disaggregated catch information based on growth curves by management unit: Restrepo et al. (2010) for the western Atlantic, and Cort (1991) for the eastern Atlantic including the Mediterranean. Both curves are derived from length frequency analysis and calcified structures age interpretations.

Several different methods have been applied to infer the age of ABFT, but the most common is counting periodic growth increments on calcified structures (Rooker et al., 2007). These structures show pros and cons for the age estimation (Rodriguez-Marin et al., 2007): otoliths and fin spines are most commonly used, but while otoliths allow age estimates for the whole age range, dorsal fin spines present nucleus vascularization which obscure early growth zones in older fishes. On the other hand growth increments on caudal vertebrae become tightly aligned at the margin and the use of scales is constrained to the first ages, up to 4 or 5 years. Furthermore age inferences from otoliths have been validated by the bomb radiocarbon method (Neilson and Campana, 2008). However otoliths also have disadvantages such as their fragility and small size and the difficulty of removing them without damaging the fish and hence

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http://dx.doi.org/10.1016/j.fishres.2015.06.002
0165-7836/

affecting its market value, making it very difficult to obtain otoliths from certain fisheries. Dorsal fin spines have proven useful in the age determination of *T. thynnus*, and progress is being made in validating age estimation from this structure in order to use spines as an alternative structure to otolith for bluefin tuna direct ageing. These steps forward consist in cohorts tracking, fin spine radiocarbon age validation and spine edge type and marginal increment formation (Rodriguez-Marin et al., 2009; Rodriguez-Marin et al., 2012b; Luque et al., 2014).

The back-calculation procedure can be defined as estimating fish length at an earlier time on the basis of a set of measurements of calcified structure size and fish length made at a single point in time (Francis, 1990). It has been used for a variety of purposes: to increase the number of lengths at age data to be used in fitting growth curves, to estimate lengths at ages that are rarely observed, to compare growth rates or to test the age estimation based on annuli (Francis, 1990). Nucleus vascularisation of first dorsal fin spiniform rays in ABFT is the major limitation in using this calcified structure for ageing purposes and may result in age underestimation or overestimation of growth, since first growth marks are missing due to nucleus vascularisation, which increases with age or fish length (Kopf et al., 2010). This reabsorption of the central portion of the first dorsal ray begins from 2 years old ABFT (Compeán-Jimenez and Bard, 1983; Rodriguez-Marin et al., 2007; Luque et al., 2014). Therefore, the measurements of the first annuli are essential to ensure the ages estimated from the rest of annuli of ABFT spine sections are estimated accurately. In this context, the back-calculation procedure will provide important information for a more robust age estimation of this species.

Until now only one back-calculation study using first dorsal rays of this species has been published (Santamaría et al., 2009), and is based on a sample from central Mediterranean, a limited area of the distribution of the eastern stock of ABFT. The present paper includes samples from both Mediterranean and Atlantic areas, and may provide better knowledge of the overall growth of the East Atlantic and Mediterranean stock. This study aims to estimate back-calculated lengths at age for obtaining new growth parameters, including lengths at young ages that are not easily obtained from medium and big ABFT fisheries; to improve the knowledge of the growth of the younger ages, providing a basis for the age estimation of the rest of annuli; and to compare the growth pattern obtained in this paper with those of previous studies.

2. Material and methods

2.1. Sampling

A total of 2678 ABFT were sampled from the North east Atlantic ($n = 2076$) and the Mediterranean Sea ($n = 602$) over a 21 year period from 1990 to 2010, including 175 samples from medium size specimens sampled in 1984 (Table 1). This wide sampling period was used with the aim of covering, as much as possible, the whole length range and all months of the year (mainly from April to November, where most of the fisheries take place). Sampling was based on port landings from different seasonal fisheries and geographic areas in the North east Atlantic and the western Mediterranean including the bait boat fishery from the Bay of Biscay, long-line fishery from the south of Island, Gulf of Cadiz and western Mediterranean and Atlantic traps near the Strait of Gibraltar.

Straight fork length (SFL) was measured in each tuna sampled to the nearest cm. Specimens caught in the North East Atlantic ranged from 53 to 287 cm SFL whereas specimens caught in the Mediterranean Sea ranged from 45 to 251 cm SFL (Table 1). This extensive data set has been partially used in some ICCAT scientific documents (International Commission for the Conservation of Atlantic Tunas, Collective Volume of Scientific Papers) and some samples were used in the study of Luque et al. (2014) for other purposes.

2.2. Age estimation and back-calculation

The first ray of the first dorsal fin (hereafter spine) was used for age estimation and to perform the annuli measurements. The procedure for preparation, age interpretation, and measurements of spine sections, described by Rodriguez-Marin et al. (2012a) and Luque et al. (2014), were followed. An annulus was defined as a wide opaque zone followed by a narrow translucent one (Compeán-Jimenez and Bard, 1983; Hurley and Iles, 1983) and age was estimated by counting the translucent bands. The total diameter of each spine section was measured at its external border, and the diameters of annuli were measured to the outer edge of each translucent zone (Fig. 1). In young individuals it is easy to identify the opaque and translucent bands formed on the spine. However, in fish older than two years old, the central area of the spine begins to reabsorb and the bands consequently disappear (Fig. 1). To overcome the problem of reabsorption of annuli with age, the translucent band diameters measured from spines without vascularization (*i.e.* spines from young specimens) were used to assign an age to the first inner visible translucent band in vascularized spines (Luque et al., 2014). Following theses authors, when the diameter of at least two of the three innermost visible bands fall within the ranges calculated from the S.D. shown in the reference table in their study, the corresponding ages were assigned. Once the age of the first inner visible translucent band was estimated, final ages were calculated by adding the number of translucent bands estimated to lie within the vascularized area and the number counted between the vascularized area and the spine edge. Nucleus vascularization represented an average loss of nearly 30% of the total number of annuli from each spine section. There was a frequent occurrence of sub-annual translucent bands in examined spine sections, these translucent bands are very close together to be considered a yearly mark and are usually distinguishable within the general pattern of band deposition. These sub-annual bands may appear before the first annulus formation and were considered as annulus 0.

In order to apply the back-calculation technique, three main assumptions have to be fulfilled (Panfili et al., 2002): the assumed time of annuli formation (translucent band) is correct and therefore it is necessary to show that there is a season of the year in which the spine forms a translucent edge; the back-calculation function accurately relates fish length to spine size for each fish, and the size of the spine mark is the same as the size of the spine at the time the mark was formed (no degeneration of the calcified structure).

2.3. Seasonality at annuli formation

The monthly proportion of edge type was examined in ABFT spine sections by Luque et al. (2014). Results from this study showed that the appearance of the translucent band occurs from September to May, with a 50% of occurrence between mid-October and May, indicating an annual periodicity in the formation of the translucent bands.

2.4. Relationship between fish straight fork length and spine radius

In order to determine the relationship between fish fork length and spine radius (measured as half the diameter), two fits by least-squares minimization algorithm were performed for 2660 pairs of values, following two regression functions:

$$-\text{linear regression}: \ \text{SFL} = a + bR \quad (1)$$