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Improving growth estimates for Western Atlantic bluefin tuna using an integrated modeling approach

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ABSTRACT

Advances in modeling growth using tag-recapture data and progress in otolith ageing procedures allowed improved fitting of the Western Atlantic bluefin tuna growth curve. Growth parameters were derived from an integrated analysis of tag-recapture data and otolith age-length data using the "Aires-da-Silva-Maunder-Schaefer-Fuller with correlation" (AMSFc) framework, which models growth such that parameter estimates from each data source are directly comparable. The otolith data consisted of a sample of 4045 otoliths for which ages were estimated using tested and consistent protocols and conventions designed to avoid bias. Strict data quality control measures were applied to the tagging data for quality assurance and a subsample of 1118 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. The Richards curve appears to provide a better fit. Both curves follow a similar trajectory until age 16, after which they diverge considerably. The Richards model supports a lower mean asymptotic length (L_∞ = 271.0 cm FL) than the model currently used in the stock assessment (L_∞ = 314.9 cm FL).

1. Introduction

Migratory pelagic fish present both opportunities and challenges in developing predictive growth models. Species such as Atlantic bluefin tuna *Thunnus thynnus* (ABT) attract substantial fishing effort, affording opportunities to access fish for tagging and collection of otoliths, which support parameterization of growth. Principal challenges include sufficient sampling, implementing quality control procedures to curtail biased observations throughout the stock's range, and making best use of combined age-length and tag-recapture data. Otolith data are used to estimate absolute ages and allow size-at-age functions to be modeled. For western ABT, these data are largely centered on the larger/older fish targeted by the recreational and commercial fisheries. Tagging data often have the opposite problem of lacking large fish and fish with long times at liberty. Each data source is also prone to various sources of observation error – mainly variability in age assignment across readers and measurement error in recorded fish lengths. It is therefore advantageous to estimate growth from both sources of data simultaneously to increase the size and representativeness of the sample and test the influence of each dataset on resulting parameter estimates (Maunder and Punt, 2013). We apply a new maximum likelihood approach to fit jointly direct age estimates, for a large sample of otoliths, with release and recapture lengths of conventionally marked fish.

ABT is the largest member of the Scombridae family. It can reach weights exceeding 600 kg (Collette and Nauen, 1983) and live over 34 years (this study). The species is assessed and managed as two distinct stocks by the International Commis-

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sion for the Conservation of Atlantic Tunas (ICCAT) under the assumption of no net mixing (ICCAT, 2014): the eastern stock (eastern Atlantic/Mediterranean) and the western stock (western Atlantic/Gulf of Mexico), with spawning grounds on opposite sides of the North Atlantic Ocean basin (Boustany et al., 2008; Carlsson et al., 2007; Riccioni et al., 2010; Richardson et al., 2016). Although these two stocks are conventionally separated by the 45°°W meridian, tagging data indicate a high degree of transoceanic migration for animals of all ages, with significant mixing occurring on foraging grounds (Block et al., 2001, 2005; Sibert et al., 2006).

Following years of overfishing, ICCAT adopted rebuilding plans for the western and eastern stocks in 1998 and 2006, respectively, gradually tightening control measures over time, as the Commission strived to meet its objectives. According to the latest stock assessment, both stocks are showing signs of recovery. Still, considerable uncertainties remain in the assessment, particularly regarding maturity, growth dynamics and the level of mixing between the two stocks, making it difficult to draw definite conclusions about the current and future status of the stock (ICCAT, 2014).

Information on age and growth is needed to assess properly a depleted stock and define its rebuilding target. This holds especially true for bluefin tuna for which a growth curve is used to translate catch-at-size to catch-at-age through cohort slicing in the stock assessment process. Being a moderately long-lived, iteroparous species, bluefin tuna relies on the periodic production of strong year classes to persist through time (Secor, 2007). In this case, it becomes particularly important to characterize precisely the age structure of the stock, since having a truncated age structure (Siskey et al., 2016) and being the target of a highly age/size selective fishery (ICCAT, 2014) can severely compromise the sustainability of the fishery.

The growth parameters currently used in the assessment of western ABT (Restrepo et al., 2010) were derived from a combination of otolith-based age readings for large fish ($n = 146$; Neilson and Campana, 2008; Secor et al., 2009) and modal analysis of length frequency data for small fish (1–3 years of age, 1970's US purse seine data). In their analysis, Restrepo et al. (2010) did not include information available in the ICCAT tagging database used to construct the former growth curve (Turner and Restrepo, 1994) due to data quality concerns and biases in the estimation process. Although the Restrepo et al. (2010) analysis was a significant improvement over the former growth curve, recent advances in integrative modeling and otolith age reading techniques highlights the need for an updated assessment of the current growth curve.

During a workshop aimed at standardizing otolith-based ageing protocols for ABT, Busawon et al. (2015) determined that the otoliths used by Restrepo et al. (2010) were significantly over-aged (average 3 years) due to errors in assignment of the first annulus. The problem was resolved using a standardized reference scale for the first annulus adopted by the laboratories involved in ageing studies (Secor et al., 2014a).

Improvements in both data quality control (Ailloud et al., 2014) and modeling techniques (Aires-da-Silva et al., 2015; Francis et al., 2016) now allow for the ICCAT tagging data to be incorporated in the growth analysis. Francis (1988) showed that growth parameters estimated from age-length data and tagging data have different interpretations when tagging data are analyzed by modeling growth increments through time (e.g., as done by Fabens, 1965). Comparing these estimates assumes that the expected annual growth of fish of age A (estimated from age-length data) is equivalent to the expected annual growth of fish whose length is equal to the mean length of fish of age A (estimated from tagging data), which is seldom the case (Francis, 1988). In recent years, maximum likelihood approaches have been developed that model the joint density of the release and recapture lengths as a function of age, making growth estimates age-based and thus avoiding the comparability problem (Laslett et al., 2002; Palmer et al., 1991; Wang et al., 1995). At the forefront of integrated methods is the so-called "Laslett–Eveson–Polacheck" (LEP) approach (Eveson et al., 2004), which models the release and recapture lengths as functions of age by treating age at tagging and asymptotic length, L_∞, as random variables. Though statistically attractive, this method can be difficult to implement due to its high computational demands and complicated error structures. A simpler alternative was developed by Aires-da-Silva et al. (2015) and later improved upon by Francis et al. (2016) by allowing correlation among deviates in tagging length: the AMSFc approach (Francis et al., 2016), named after Aires-da-Silva, Maunder, Schaefer and Fuller, where "c" stands for correlation. Like the LEP approach, this method also treats pairs of observed lengths as a function of age, but treats L_∞ as a fixed parameter, greatly reducing the computational demands of the model (Aires-da-Silva et al., 2015). The AMSFc approach is applied here to fit and compare alternative growth models for the western stock of ABT.

2. Materials and methods

2.1. Tagging data

The ICCAT conventional tagging database combines tag release and return information from several tagging studies conducted in various regions of the North Atlantic Ocean over the past 75 years. Of more than 85,000 releases, ICCAT recovered information for nearly 6000 recaptures, of which 2434 had complete and plausible data (e.g., non-negative times at liberty) on the date and length at release and recapture. Ailloud et al. (2014) demonstrated that the database contains valuable information for estimating growth of bluefin tuna (such as records of fish that were at liberty for many years and of old fish which appear to have reached their maximum sizes), but that extraction of the data must be done with care. Quality control measures employed in our analysis are detailed below (applied to data from the 06/30/2016 database update).

Animals at liberty for less than 105 days (~3.5 months) were excluded from the analysis (1068 records) since, a) for fish with short times at liberty, the observed growth increments largely represent measurement error rather than somatic growth (Ailloud et al., 2014) and b) stress related to the tagging event could potentially have an adverse effect on growth in the short run.

Records showing the fastest and slowest 2% absolute growth per day were removed in an attempt to eliminate outliers (i.e., data entry misrecordings and large measurement errors) and improve growth parameter estimates (116 records dropped). To test the sensitivity of the results to these outliers, a separate run that included the outliers was performed.

Fish both captured and recaptured in the eastern Atlantic, as well as fish either captured or recaptured in the Mediterranean, were excluded from the analysis (132 records). This rule does not guarantee that fish of eastern origin are removed from the sample since considerable mixing is known to occur (Siskey et al., 2016), but it instead attempts to keep the tagging data sample focused on fish present in the western Atlantic, since growth is presumably linked to local conditions (e.g., prey abundance, water temperature and fish density).

The resulting dataset consisted of 1118 records with lengths at tagging ranging from 36 to 259 cm FL, lengths at recapture ranging from 53 to 292 cm FL (Supplementary Fig. A1) and times at liberty ranging from 4.5 months to 16 years (median = 1 year). Fifty three percent of the records corresponded to fish tagged in the 1960's, another 43% corresponded to fish tagged in the 1970's and the remaining 4% were released between 1980 and 2011.