SCRS/2023/038 Collect. Vol. Sci. Pap. ICCAT, 80(4): 83-96 (2023)

BLUE SHARK: AGE AND GROWTH FROM ICCAT CONVENTIONAL TAG DATA

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SUMMARY

This paper analyzes conventional blue shark tagging-recapture records available in the ICCAT database, providing estimates on the growth of this species. Sensitivity analyses were tested selecting different datasets, several transformation equations between TL and FL, a wide range of FL_0 values and applying different fitting models. Growth results were compared with each other and with those described by other authors. Historical FL_{max} values were also reviewed and discussed. The results obtained using several non-linear fits were very similar to each other and generally produced growth models with higher k values and faster growth than those described by other authors using reading-interpretations on vertebrae.

RÉSUMÉ

Ce document analyse les registres de marquage conventionnel-récupération de requins peau bleue disponibles dans la base de données de l'ICCAT, fournissant des estimations sur la croissance de cette espèce. Des analyses de sensibilité ont été testées en sélectionnant différents jeux de données, plusieurs équations de transformation entre TL et FL, une large gamme de valeurs de FL0 et en appliquant différents modèles d'ajustement. Les résultats de croissance ont été comparés entre eux et avec ceux décrits par d'autres auteurs. Les valeurs historiques de FLmax ont également été examinées et discutées. Les résultats obtenus en utilisant plusieurs ajustements non linéaires étaient très similaires les uns aux autres et produisaient généralement des modèles de croissance avec des valeurs de k plus élevées et une croissance plus rapide que ceux décrits par d'autres auteurs utilisant des interprétations de lecture sur les vertèbres.

RESUMEN

El presente documento analiza registros de marcado-recaptura convencional de tintorera disponibles en la base de datos de ICCAT y proporciona estimaciones del crecimiento de esta especie. Diferentes análisis de sensibilidad fueron ensayados seleccionando distintos sets de datos, varias ecuaciones de transformación entre TL y FL, un amplio rango de valores FL_0 y aplicando diferentes modelos de ajuste. Los resultados del crecimiento fueron comparados entre ellos y con los descritos por otros autores. Valores históricos de FL_{max} fueron también revisados y discutidos. Los resultados obtenidos usando varios ajustes no lineales fueron similares entre ellos y en general produjeron modelos de crecimiento con valores de k más altos que los descritos por otros autores usando lecturas interpretativas sobre las vértebras.

KEYWORDS

Tagging-recapture, blue shark, age, growth

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1. Introduction

Tagging-recapture programs conducted using conventional tags on tuna, tuna-like species and large pelagic sharks were began and developed in the Atlantic at the beginning of last century mainly in North-western regions. Tagging studies specifically targeting sharks began in the late 1920's and today numerous cooperative shark tagging programs exist Worldwide (Kohler and Turner 2001). These programs were largely increased since 1960's (Casey 1985, Kohler *et al.* 2002). The last authors already indicated a total of 91,450 blue sharks tagged-released between 1962 and 2000 of which 5,410 blue sharks had been recaptured during that period. Fishermen participating in that program have tagged over 300,000 sharks and recovered over 18,000 of thirty shark species[2]. The purpose of those tagging programs on sharks was to gain knowledge of these species and broaden the scope of the tagging-recapture activities started by several countries (*i.e*. Casey 1985, Kohler *et al.* 2002). Recreational fishermen tagged around twenty thousand blue sharks between 1970 and 2013 off the coast of Ireland, which accounts for 45% of all tagged fish since the beginning of that programme[3] (Wögerbauer *et al*. 2016). Scientists and crews of the Spanish longliners voluntarily began swordfish tagging programs in Eastern Atlantic in 1981 and they were extended to sharks and other species (García-Cortés *et al.* 2000, 2003; Mejuto 1991, Mejuto *et al.* 2005, 2008). All those tagging programs (*inter alia*) included scientific tagging surveys, opportunistic tagging done by scientific observers on board and by skippers and sailors of commercial and recreational boats.

One of the most important aspects of the conventional tagging programs carried out on an international level is the availability of the appropriate resources to be able to recover the tags implemented and receive complete and accurate information of recaptures. In that sense, it is essential to have an adequate and collaborative system (Holt 1963) as well as rewards, lottery, etc., to improve returns of tagged fish (Hylen 1963). An ICCAT tagging coordination meeting was done in 2007 (Anon. 2008). After reviewing the tagging programs conducted, the group proposed some recommendations for harmonizing systems. Those actions have already improved some protocols. However, the systems and rewards for recovering the conventional tags are not fully harmonized so far and it is not efficient in some cases, which give rise to feelings of animosity among crews, depending on the type of tag recovered, the flag of tagging or recapture, the real availability of rewards, the species recaptured, etc.; occasionally leaving the laboratories to deal with unpleasant situations when contacting the fishermen for reporting the recaptures. The pressure from the public opinion, restrictive or poorly designed management actions can in some cases discourage fleets for reporting accurate data (Cortés 2017) but also the numbers of tags applied and the recaptures reported. The protocols kept in each country and the close relationship between fishermen and scientists are usually more important than rewards, at least in many countries where rewards for recovering conventional tags are so far merely symbolic and the scientific interest prevails over other factors. Recovery rates are also in some cases minor because the lack of awareness about this scientific activity or suspicion about the use of the information obtained. This could explain why some fleets with high fishing intensity are not necessarily those that contribute to higher reporting rates or only scarce reports are available.

Thanks to the close communication and collaboration between scientists and fleets maintained in some cases over the course of several decades, great progress has been made in number and quality of blue shark recoveries reported from some laboratories. However, the available data are not fully merged, databases are not standardized or they have incomplete details in many ICCAT records, sizes are omitted or reported in different units, etc. The sources of information are still scattered, and filtering processes are not fully implemented in many cases before reporting by national scientists or CPCs.

Tagging fishes with conventional tags is a method regularly used to gain insight into horizontal migrations and mixing as well as applied to growth studies and validation (*inter alia*). Moreover, it is a tool regularly used in conjunction with other methods, such as electronic tagging, genetic techniques, etc., in stock structure research. Conventional tagging has long-term advantages over other techniques, but it also has its limitations. Both pros and cons should be taken into account when planning experiments and analysing the results obtained from conventional tagging-recapture data. The tagging strategy such as the selection of areas-seasons and the type of tag used, among other factors (including habitat conditions and fisheries developed by area) they could significantly influence the recapture patterns and rates achieved.

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[2] https://www.fisheries.noaa.gov/feature-story/john-jack-casey-internationally-recognized-shark-researcher-mentor-and-narragansett
[3] https://www.fisheriesireland.ie/species/blue-shark-prionace-glauca

The abundant blue shark species is currently being tagged by many different organizations in many parts of the world, and fishermen and fish handlers of many nations have the opportunity of encountering tagged fish. ICCAT has developed since many decades an international-cooperative tagging program in the Atlantic Ocean and its adjacent seas (Ortiz *et al.* 2023 in press) and many improves have been done. However, one of the most important programs on blue shark was probably developed during many decades by Dr. Casey *et al*. (Narragansett Laboratory, Rhode Island) and this and other huge collaborative international actions during long time have probably not been sufficiently recognized by the international scientific community. Tagging-recapture blue shark data are so far relatively scarce o minor from South Atlantic areas (Anon. 2015).

One of the objectives of the present paper is to conduct an exploration of the growth rates of blue shark inferred from tagging-recapture information available in the ICCAT database over decades of collaboration with the fleets of different national and international research centres on recaptures of blue shark. A more comprehensive exploration of all the dataset would require a full and in deep revision of the incomplete data provided by national scientists and laboratories, and probably developing collaborative projects to be started that would allow the correction of records reported and the joint analysis of the huge effort that has been made by many different scientists and laboratories for decades. This paper attempts to summarise progresses made on growth rates inferred from the ICCAT tagging-recapture database of blue shark as well as to discuss how the tagging-recaptured data could be used as a method of estimation and validation for growth and to venture diagnosis that will serve to orient further studies and stock assessments.

2. Material and methods

The data source used for the present analyses is the tagging-recapture BSH file (ICCAT.DB, as of 2023.01.31) published on ICCAT web site. A first data filter was made taking into account records with tagging date, recaptured date, length at tag-release and length at recapture information filled. Records with less than one year at liberty were not taken into account since the relative important bias estimation of the length at release would greatly influence the estimation of the initial growth rates, producing large amount of the biologically-inconsistent negative growth rates inferred also pointed out by other authors (Carlson *et al.* 2023 in press, Ortiz *et al.* 2023 in press). In order to unify the measurement units, records reported as Fork-Length (FL) or Straight Fork Length (SFL) were considered as FL (cm). Many records reported to ICCAT as FL are really SFL. Additionally, the difference between SFL and FL is relatively minor in blue sharks than in other species such as tunas or shortfin mako due to the body morphology of the blue shark, especially for those sizes regularly available in tagging-recapture data. Therefore, this assumption is considered to have little impact on growth results obtained. Those specimens reported in other type of length were converted to FL cm applying different published equations:

Eq1: $FL = -1.061+0.8203*TL$	Castro and Mejuto (1995)
Eq2: $FL = -1.2+0.842*TL$	Campana *et al*. (2005)
Eq3: $FL = 0.8313*TL+1.39$	Kohler *et al*. (1995)
Eq4: $FL = -1.358+0.83264*TL$	Mas *et al*. (2014)

Growth rates and growth models were obtained from this dataset using both linear fit and maximum likelihood approaches. Von Bertalanffy growth functions (von Bertalanffy 1938) were fitted to length-at-age data fixing FL_0 values following a transformation of that equation (Fabens 1965): $FL_t = FL_\infty - (FL_\infty - FL_0) * e^{-k*t}$

Where FL_t = predicted length at time t; FL_∞= mean asymptotic fork length; k= growth rate parameter (yr^{-1}); and FL_0= the FL length at birth.

The Gulland and Holt (1959) linear method uses graphical interpretation of the tagging-recapture data to produce estimates of FL_∞ and k. The annual growth rate (cm/yr) was plotted against average FL (cm) between tagging and recapture to calculate linear regression coefficients. The slope is equal to –k and the x-axis intercept is equal to FL_∞ (Sparre and Venema 1998). It was compared how both different values of FL_0 and the different approaches in the length transformation (TL converted to FL) influence the estimation of growth equations. Several published growth models were also compared each other and with those obtained in the present study. Moreover, an analysis of our available tagging-recapture records of blue shark was specifically done to be compared to those obtained using the full ICCAT dataset.

Records selected were also analyzed using functions '*grotagplus*' and '*growhamp*' from the library '*fishmethods*' in R.4.2.2 which implements several fitting methods. FL_{max} data obtained by Spanish observers at sea was also reviewed and discussed. Theoretical longevity (T_{max}) was calculated according to Taylor (1958) and Fabens (1965) as the age at which 95% or 99% of the maximum asymptotic length is reached, and compared with real data. A modification of the Taylor (1958) equation (Natanson *et al.* 2006) was used to obtain longevity when FL_0 replaced t_0.

$$T_{max} = t_0 - \frac{\ln(1-0.95)}{k} \quad \text{Taylor (1958)}$$

$$T_{max} = 5 * \frac{\ln(2)}{k} \quad \text{Fabens (1965)}$$

3. Results and discussion

A total of 143,908 records are in the tagging BSH file (ICCAT.DB, as of 2023.01.31) published on ICCAT web site; 10,195 of them correspond to recaptured specimens, but 2,867 were the records that remained after the first data filtering (records with date and length information on tagging and recapture, and with one or more years at liberty).

The first analyzes carried out were to verify sensitivity about how different FL_0 values influence the estimation of the growth model. Several authors have estimated different L_0 values from 34.7 cm FL (Mas 2015) to 62.3 cm FL used in the 2015 ICCAT stock assessment (Courtney 2016). To minimize possible interferences, only 1,136 records with both tagging and recapture length units in FL were taken into account to calculate the linear regression coefficients. **Figure 1** shows how values from 40 to 55 cm FL_0 influence the growth model estimated using these coefficients. The results suggest a maximum variation of 12.5 cm FL in the first year of life, being less than 5cm FL after the fifth year. Different studies have shown some specimens caught by surface longlines with sizes smaller than 60 cm FL (García-Cortés *et al*. in press 2023, Coelho *et al*. 2017), the maximum embryos sizes reported was lower than that size (Castro and Mejuto 1995) and some specimens sighted in the wild or caught with other fishing gears from 40 cm TL (Mejuto *et al*. 2014, Bañón *et al*. 2016). Additionally, the minimum tagged-released individual reported in the ICCAT dataset was at 50 cm SFL (Ortiz *et al.* in press 2023). So, for the rest of analyzes, a value of FL_0 equal to 48 cm was used (Mejuto and García-Cortés 2005).

Figure 2 shows how the TL to FL transformation equations, or taking into account only records with positive growth without other data cleaning, influence the growth curves inferred. No significant differences are really observed during the first 5 years of life in terms of the transformation equation selected; however it does affect the use of only the records with positive growth for estimating a FL_∞ up to 430 cm.

Data from tagged-recapture specimens with one or more years of liberty, positive growth rates and FL cm length units were analyzed. **Figure 3** represents the box-plot of the annual growth rate for each FL 5cm length class. In addition to the detected outliers, there are very large individuals with high growth rates and small individuals with small growth rates which are biologically inconsistent and they could be review and removed from analyses.

Figure 4 shows the calculated growth curves using the Gulland and Holt (1959) linear method for three different data sets: (1) records with one or more years of liberty, positive growth, FL cm length units and outliers removed, (2) records with one or more years of liberty and FL cm length units and (3) records with one or more years of liberty and using Kohler *et al.* (1995) TL to FL transformation equation when necessary. The sensitivity linear analyses using our blue shark tagging-recapture dataset have produced almost identical results than using the full ICCAT dataset. Over 39% of available ICCAT records with tagging and recapture data have been provided by each the Spanish and the US fleets, which both together are representing the 79% of those available records. Nonetheless, only 24% of those records reported by the US fleets had a release period equal to or greater than one year, while the recaptures reported by the Spanish fleet reached 63% of the recaptures longer or equal one year after released. So, most of that records form US fleets in the ICCAT dataset are regularly representing short time periods -less than one year after released- and short linear distances -regularly less than 700 nm-; while the Spanish fleet records are regularly representing longer periods and broader horizontal migrations. Moreover, considering those records with both available dates and sizes of tagging and recapture, the availability of records corresponds 57% and 25% to the Spanish and US fleets, respectively. The preliminary revision of the

ICCAT dataset, considering the long history of some tagging programs carried out on blue shark (see introduction) and considering the analyses and the summary recently carried out (Ortiz *et al.* 2023 in press) are probably suggesting lacks of some data and many incomplete records in the ICCAT database which could be available in some national programs but that have not yet been full reported to ICCAT.

The records from *dataset 1* were analyzed using maximum likelihood approach (Francis 1988) with *grotagplus* function and also using *growhamp* functions for other fit models. Between the models tested with *growhamp* function, the best AIC was obtained from *Sainsbury with ME* model. However, differences in the predicted size-at age between those models were in fact minor for the most prevalent sizes-ages described in Task-2-size ICCAT datasets. **Figure 5** shows the growth curves obtained with the different fit methods tested.

Growth curves estimated in the present study were compared with others previously published (**Figure 6**). The results obtained in the present paper using non-linear fits were very similar among them and generally have produced growth models with higher k values and faster growth than those described in literature review which have used reading-interpretations of bands on vertebrae. A similar finding was recently described when both methods are compared by the same authors (Carlson *et al.* 2023 in press).

Table 1 summarizes the von Bertalanffy constants of the different growth functions included in **Figure 6** and their theoretical longevities (T_{max}). The revision of our FL_{max} values recorded over time considering only data from scientific observers at sea have provided sizes of 310 cm for females and 298 for males. These values are close or in the range of the most FL_{∞} values obtained in the present study. In that sense, a recent revision of the tagging-recapture ICCAT dataset (Ortiz *et al.* 2023 in press) indicated SFL_{max} values of 429 cm and 535 cm for size at release and recapture, respectively; however these records should be verified.

Table 2 summarized the size at first maturity (FL_{50}) described in literature by several authors. The size of maturity estimated by those authors was between 163.0 and 191.7 FL cm for females and between 168.8 and 197.5 FL cm for males. The variability of this value is depending of the availability of respective samples in each study. One of the most comprehensive studies covering broad areas of the Atlantic, Indian and Pacific (Mejuto and García-Cortés 2005) indicates mean FL length values of observed females with embryos in defined Atlantic regions between 206 and 219 FL cm with mean litter sizes between 34 and 39 pups, but females with embryos appear in highly significant numbers when females reach roughly 150 FL cm.

The selection of growth parameter is very important in the case of those stock assessment models that incorporate this parameter as well as for interpreting other models tested. Sometimes, it is argued that the size data at tagging and releasing are in many cases estimated, while in other cases the size is well measured by the tagger. Assuming this possible source of uncertainty, it is expected that the underestimations of the size at release would be compensated by the overestimations of the size at release. Rarely, this type of uncertainty would significantly affect the sizes recorded at the time of recapture. Consequently, it is not expected that this possible source of uncertainty during tagging would have substantial effects on the mean growth estimates obtained, especially when a data filter is excluding those fish that have had very short release periods. Although the sources of uncertainty should be considered in all growth studies based on tagging-recapture, the uncertainty should be also considered in studies carried out using other methodologies. In that sense, Natanson *et al.* (2018) points out some possible sources of uncertainty when reading hard structures of sharks and summarizes relevant issues related to the band interpretation on vertebrae of several shark species including the blue shark, pointing out subjectivity within vertebral band interpretation in age and growth studies because that interpretations are subjective and contingent on several factors, including the preparation method, microscope quality, computer hardware, image analysis programs and reader experience, among other cited. These authors also pointed out that the relationships between band depositions to time must be considered *loosely correlated* over the span of the studies because they have shown changes in the counts along the vertebral column and ontogenetic changes in band deposition rates observed. Therefore, those authors conclude that band and band pairs are not necessarily linked to time related events and some of the techniques suggested for validations could neither provide a real validation. Although the hard structure in blue shark seems to be more consistent than in other sharks species studied by these authors, the validation of the methodology used (Skomal and Natanson 2003) was weak, just from a couple of fish.

Taking into consideration those conclusions and despite some limitations in the currently available ICCAT tagging-recapture dataset of blue shark, the number of available and useful record is relatively high and probably much higher than in many other ICCAT species. Growth studies based on tagging-recapture are postulated as a good candidate to empirically understand and verify the growth of blue shark. With all this in mind and based on previous studies, this recommendation seems to be reasonable regarding facing growth estimates based on tag-recapture datasets compiled at least from mid 1900's onwards through international cooperation for the data provision of recaptured fish to many laboratories and to ICCAT (Ortiz *et al.* 2023 in press). Those records could help to elucidate mainly the growth of the Northern stock since most of them are coming from tagging-recapture activities occurring within and between the North Atlantic areas. But important differences in growth and other biological parameters between the Atlantic stocks are unlikely considering the very broad distribution of this species and the mixing described by tagging-recapture data. In any case, it is necessary to recover, merge, review and reconstruct many unreported, poorly verified or incomplete records. This requires hard work both by national scientists and by the ICCAT Secretariat, which they need the corresponding means and financial support.

Unfortunately, the conventional tagging activities appear to have declined in recent periods at least in the number of records submitted to ICCAT. Probably, this fact is partly motivated by the low prestige and lack of funding on these activities and the greater prestige and short-term results using electronic tagging techniques. Far from being exclusive activities, both tagging techniques should be recognized as been complementary and useful.

Acknowledgments

The authors would like to give their warmest thanks to all members of the teams who were involved in taking, recovering, recording, preparing and processing the basic tagging-recapture data used in the present paper, including the staff of the ICCAT Secretariat. We would also like to thank to all scientists that during decades have developed tagging-recapture collaborative programs providing data. We also thanks the skippers of the Spanish longline fleet for their voluntary contribution in tagging and recapture activities maintained during decades as well as in their scientific contribution to increase the knowledge on this species. This scientific work has been carried out within the CCLLSWO Research Group of the Spanish Institute of Oceanography.

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Table 1. Comparison of von Bertalanffy growth function parameters obtained in the present study and previous studies for blue shark in Atlantic Ocean and the theoretical longevity (T_{max}). Kohler equation was used to convert TL to FL values, when necessary. *values indicate the FL_0 (cm) used in Taylor' T_{max}, instead of t_0.

Study	N	Length range	Data/Method	k	t_0	FL_∞	T_{max} Taylor	T_{max} Fabens
Aasen (1966)	268			0.13	-0.80	329	21.7	26.1
Aires-da-Silva (1996)	308			0.14	-1.08	284	20.6	25.1
Henderson *et al.* (2001)	159	64-228 (TL)	vertebrae	0.12	-1.33	314	23.7	29.0
Hsu *et al*. (2015), Joung *et al*. (2017)	742	100-325 (TL)	vertebrae	0.13	-1.31	294	21.6	26.6
Jolly *et al*. (2013)	197	72-313 (TL)	vertebrae	0.12	-1.66	260	23.3	28.9
Lessa *et al*. (2004), Hazin and Lessa (2005)	236	173-310 (TL)	vertebrae	0.16	-1.01	294	17.7	21.7
MacNeil and Campana (2002)	185	145-282 (TL)	whole vertebrae	0.68	-0.25	251	4.2	5.1
			sectioned vertebrae	0.58	-0.24	252	4.9	6.0
Mas (2015)	818	65-264 (FL)	vertebrae	0.10	-1.25	290	28.1	34.0
Montealegre-Quijano *et al*. (2014b)	837	73-262 (FL)	vertebrae	0.15	-1.50	265	18.6	23.3
Skomal (1990), Skomal and Natanson (2003)	411	49-312 (FL)	vertebrae	0.17	-1.43	287	16.2	20.4
Stevens (1975)	82	42-272 (TL)	vertebrae	0.11	-1.04	353	26.2	31.5
Assessment 2015 - Courtney (2016)				0.16	62.3*	296	17.2	21.7
Present study - ICCAT tag-recapture data	1136	30-343 (FL)	Gulland and Holt	0.17	48*	341	16.9	20.5
			Francis	0.31	48*	270	8.9	11.1
			Faber	0.32	48*	269	8.9	11.0
			Kirkwood and Somers	0.34	48*	265	8.1	10.1
			Kirkwood and Somers with ME	0.32	48*	268	8.7	10.8
			Sainsbury	0.27	48*	293	10.4	12.8
			Sainsbury with ME	0.31	48*	277	9.0	11.1

Table 2. Size at maturity (FL_{50}) FL cm of Atlantic blue shark described in references consulted.

Ocean/Area	Study	Females (FL cm)	Males (FL cm)
North West Atlantic	Pratt (1979)	185	180
North West Atlantic	Viducic (2021)	190.9	192.5
Gulf of Guinea	Castro and Mejuto (1995)	180	-
Gulf of Guinea	Kouamé *et al*. (2019)	182	178
Tropical Eastern Atlantic	Wu *et al*. (2020)	191.7	197.5
South West Atlantic	Lessa *et al*. (2004), Hazin and Lessa (2005)	190.9	188.4
South West Atlantic	Montealegre-Quijano *et al*. (2014a)	171.2	180.2
South West Atlantic	Legat and Vooren (2004)	177	173
South West Atlantic	Mas *et al*. (2023)	183.8	184.4
South Africa	Jolly *et al*. (2013)	163.0	168.8

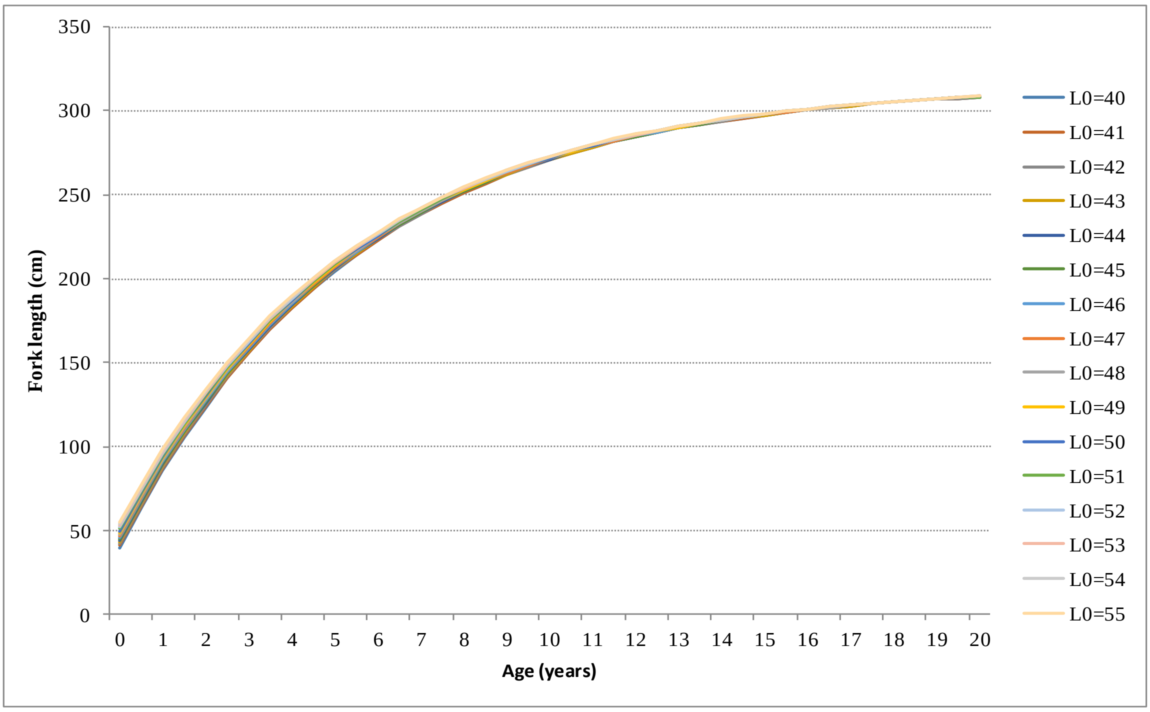

Figure 1. How different FL_0 value affects the growth curve estimations using linear fits.

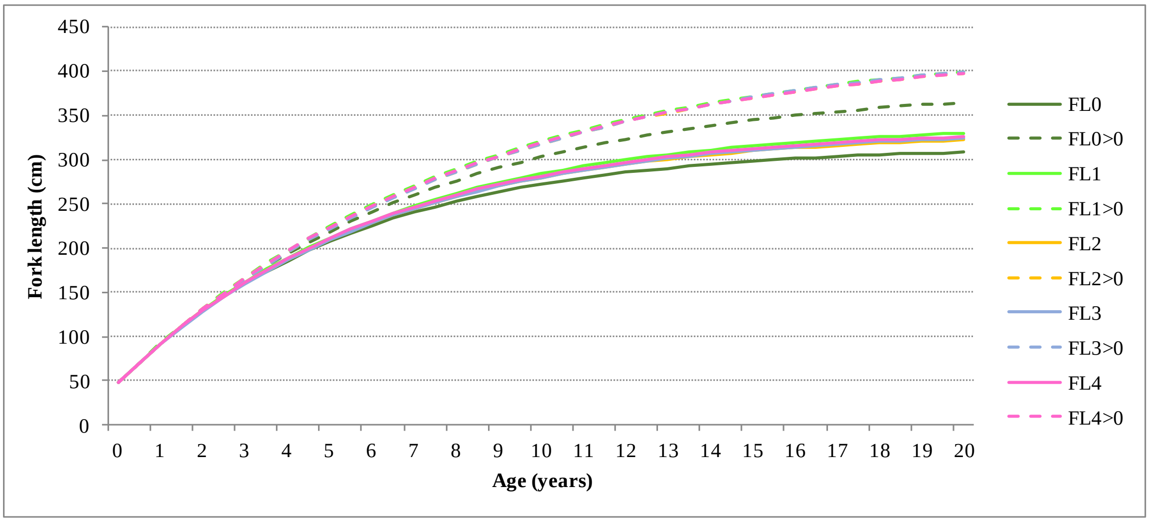

Figure 2. How the TL to FL transformation equation used, or taking into account only records with positive growth without other data cleaning, influence the growth curve. FL0=only records measured in FL units. FL1=transforming TL to FL using Castro and Mejuto (1995) equation. FL2=transforming TL to FL using Campana *et al*. (2005) equation. FL3=transforming TL to FL using Kohler *et al*. (1995) equation. FL4=transforming TL to FL using Mas *et al*. (2014) equation. FLx > 0 using only records with positive growth.

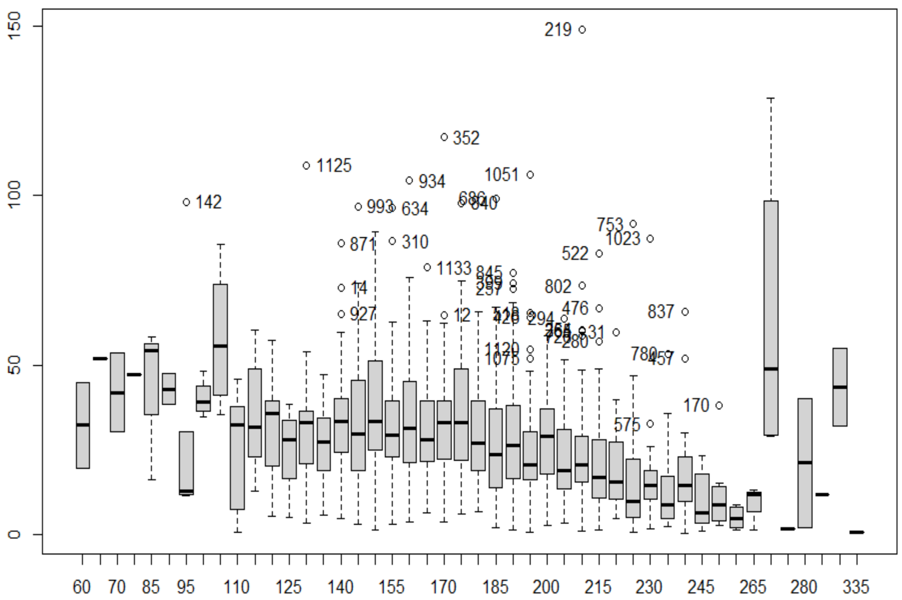

Figure 3. Box-plot of the annual growth rate (FLcm /yr) for each FL 5cm length class.

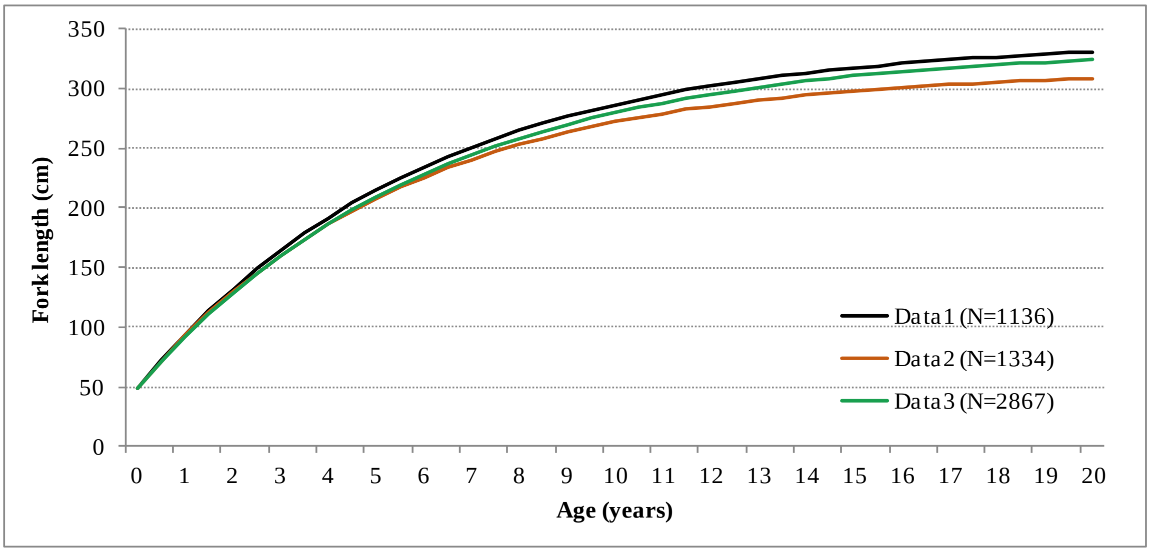

Figure 4. Different growth curves inferred from linear fits using different filtering of data source. Data1= records with one or more years of liberty, positive growth, FL cm length units and outliers removed. Data2= records with one or more years of liberty and FL cm length units. Data3= records with one or more years of liberty and using Kohler *et al*. (1995) length transformation equation when necessary.

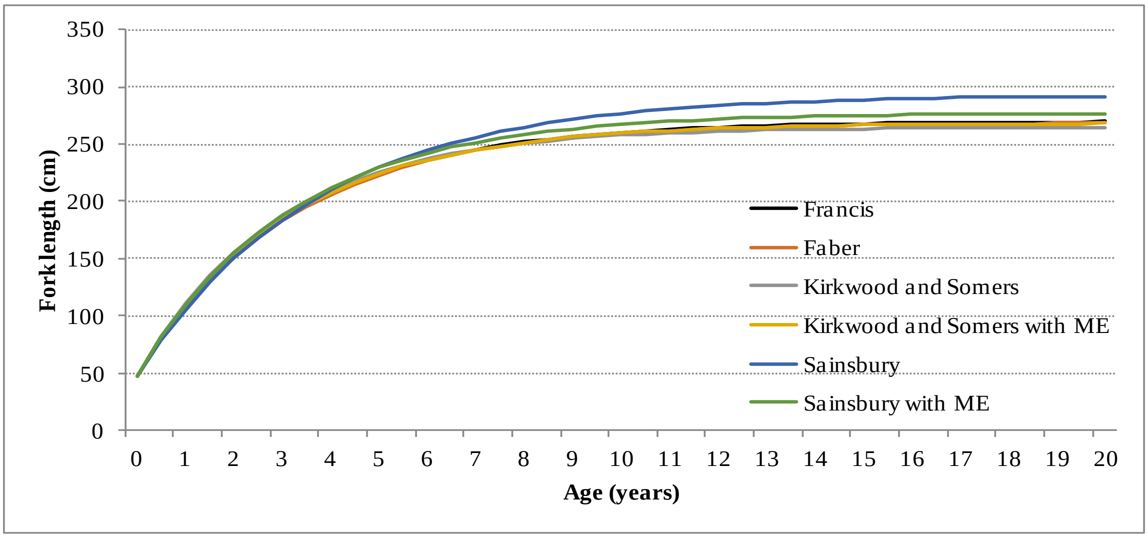

Figure 5. Different growth curves inferred from '*grotagplus*' and '*growhamp*' functions.

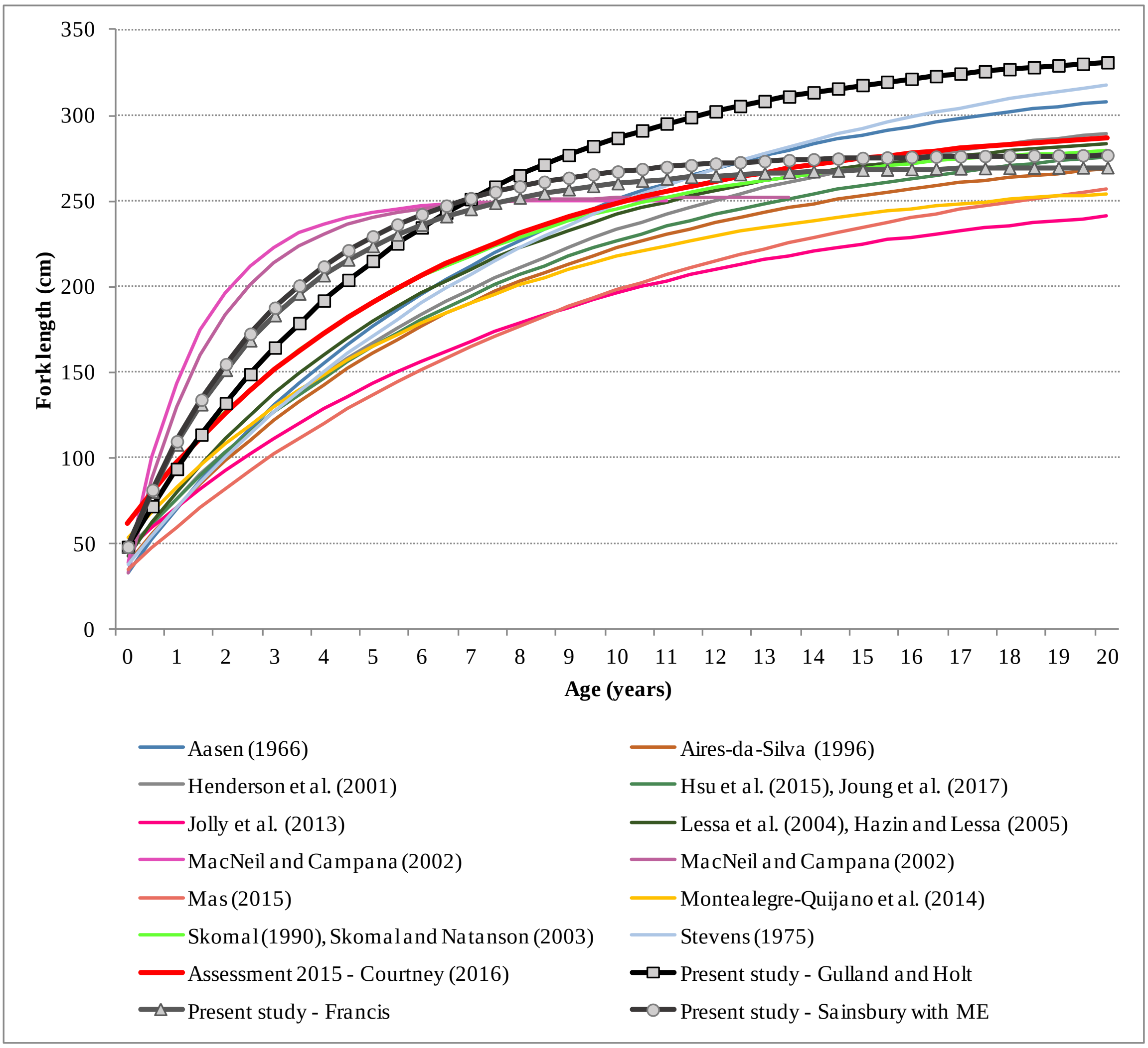

Figure 6. Comparative of present study using different fits with other published growth functions.