

PRELIMINARY ESTIMATION OF GROWTH PARAMETERS FOR ATLANTIC YELLOWFIN TUNA FROM TAG-RECAPTURE DATA

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SUMMARY

Tag-recapture data of Atlantic yellowfin from the ICCAT tagging database was used to estimate and revise preliminary growth parameters using methods that account for individual growth variability. Nominal growth rates suggest that Atlantic yellowfin tuna show a decrease in growth rates at about 50 to 60 cm FL, similar to the patterns seen in the Indian Ocean. Parametric growth models were fitted and evaluated using maximum likelihood methods that model the joint density distribution of release and recapture lengths as a function of age by assuming age at release as random variable. A two stanza growth model with a logistic transition was also investigated but preliminary results are sensitive to input parameters, likely as a result of high variability in the data a limited number of long-term recoveries.

RÉSUMÉ

Les données de marquage-récupération de l'albacore de l'Atlantique provenant de la base de données de marquage ICCAT ont été utilisées pour estimer et réviser les paramètres de croissance préliminaires en utilisant des méthodes qui tiennent compte de la variabilité individuelle de la croissance. Les taux de croissance nominale donnent à penser que l'albacore de l'Atlantique présente une diminution des taux de croissance à environ 50 à 60 cm FL, ce qui est similaire aux tendances observées dans l'océan Indien. Des modèles de croissance paramétriques ont été ajustés et évalués en utilisant des méthodes de vraisemblance maximale qui modélisent la distribution de la densité conjointe des tailles au moment de la remise à l'eau et au moment de la récupération comme une fonction de l'âge en postulant l'âge au moment de la remise à l'eau comme variable aléatoire. Un modèle de croissance à deux stances avec une transition logistique a également été étudié, mais les résultats préliminaires sont sensibles aux paramètres d'entrée, probablement en raison de la grande variabilité dans les données et d'un nombre limité de récupérations à long terme.

RESUMEN

Se utilizaron los datos de recuperación de marcas de rabil del Atlántico de la base de datos de marcado de ICCAT para estimar y revisar parámetros de crecimiento preliminares utilizando métodos que consideran la variabilidad de crecimiento individual. Las tasas de crecimiento nominal sugieren que el rabil del Atlántico presenta un descenso en las tasas de crecimiento al llegar a entre 50 y 60 cm LF, un patrón similar al observado en el océano Índico. Se ajustaron y evaluaron los modelos paramétricos de crecimiento, utilizando métodos de máxima verosimilitud que modelan la distribución conjunta de densidad de las tallas liberadas y recuperadas como una función de la edad asumiendo la edad de liberación como variable aleatoria. También se investigó un modelo de crecimiento en dos estancias con una transición logística, pero los resultados preliminares son sensibles a los parámetros de entrada, probablemente debido a la elevada variabilidad en los datos generada por el número limitado de recuperaciones a largo plazo.

KEYWORDS

Growth, yellowfin tuna, tagging, tag-recapture

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1. Introduction

Tagging data has been commonly used to estimate growth parameters of fish stocks (Fabens 1965, Francis 1988). With the advantage of efficient solution maximization routines different growth models can be analyzed with tag-recapture data (Francis 1988). Indeed, for yellowfin from the Indian Ocean, growth parameters have been estimated based on tag recapture data from a large scale tuna tagging project (RTTP-IO) (Eveson and Million 2008, Eveson et al. 2015). The ICCAT tagging database comprises a compendium of both scientific and opportunistic tagging programs in the Atlantic area as submitted by CPCs. About 18,000 yellowfin have been tagged and resealed in the Atlantic Ocean, of these 1569 fish were recaptured. However, it is important to note that the tagging data represents very diverse projects; some scientific tagging programs others more opportunistic in nature, with different type of tags, gears of release and recapture, reporting accuracy and completeness, etc. Thus, results presented here should be considered carefully and preliminary in nature. On the other hand, the tag-recapture data represents several decades of tagging, having a wide spatial coverage, and tagging also a wide size range of fish by diverse fishing gears, a detailed review of the yellowfin tag release and recaptures information used in this document is presented in Ortiz 2016.

2. Data

Tag-recapture data of Atlantic yellowfin was assembled from the ICCAT database from 1954 up to 2014. The data appropriate for growth analysis was restricted to observations where size and date were provided for both release and recapture events. Furthermore, obvious outliers were revised / updated prior confirmation with national scientist, or excluded if couldn't be confirmed.

As large proportion of the yellowfin tag-recapture data comes from opportunistic programs (USA CTC/TBF mainly) where the size measurements are estimated by fishers (commercial or recreational), size data was standardized to FL units and round to 1 cm values. It was not possible to discern between measures from scientific programs and opportunistic tagging. No conversion of size type was applied for TL or LJFL measurements. Observations were excluded when the annual growth rates (change in FL cm/year) was greater than 122 cm FL (50% of the asymptotic size of current growth model) as considered outliers, likely due to error in measure, type of measure reported, or coding. Finally, tag-recapture was also restricted to those fish that were at large for at least 1 month.

After screening, a set of 486 observations with complete dates of release and recapture, and sizes of release and recapture, respectively was assembled. **Figure 1** shows the size frequency distribution of the YFT tag-recapture data for releases (solid bars) and recaptures (shade lines). The distribution of time at large (years) is shown in **Figure 2**, and the spatial distribution of tag releases is shown in **Figure 3**.

3. Methods

Tag recapture data, basically the change in size of a tagged animal between release and recapture is commonly used to estimate fish growth. As the age of the fish at release is unknown, the traditional approach is to model the incremental in size over the time at large (Fabens 1965, Francis 1988). This approach, however results in biased estimates of growth parameters due to individual growth variability (Sainsbury 1980, Wang 1998). It has also been shown that growth parameters estimated from direct ageing are different to estimates from tag recapture data are not directly comparable (Francis 1988). Recently, maximum likelihood approaches have been developed that model the joint probability density of the releases and recapture lengths as opposed to modelling the length increment (Wang 1998, Laslett et al 2002). In these approaches, age at release is considered a random variable and individual growth variability is accounted for. However, the estimation process requires both determining an appropriate form for the growth model and a statistical procedure for fitting the data to the selected model.

A wide variety of parametric models has been used to model fish growth, with the von Bertalanffy growth model as the most commonly used. Yet other models such the generalized von Bertalanffy, the Richards, the Gompertz and logistic models had also been used in many cases with tag recapture data. Indeed, fish growth could be modeled by any cumulative statistical distribution with an asymptotic length, but is often preferred models with some biological parametric explanation. Traditionally fish growth is modeled as a continuous, smooth, monotonically decreasing function of age. However, recent analysis and studies on growth for tuna species in particular such as southern bluefin tuna (Hearn and Polacheck, 2002), bigeye tuna and yellowfin tuna (Eveson et

al 2015, Eveson and Million 2008) suggest that there is a marked change in the growth process somewhere during the transition from juvenile to subadult/adult part of the life cycle. This change implies at least a two-stage of growth where the annual increment of size decreases substantially during the transition period and thereafter it resumes until reaching the asymptotic length. There are however, problems with modelling and statistically fitting this type of complex growth models and providing a reasonable biological interpretation (Hearn and Polacheck 2002, Chassot et al 2008).

A range of growth functions were fitted to the Atlantic YFT tag recapture data using maximum likelihood approaches. Fitting started with the Fabens method to get initial estimates and starting growth parameters for more complex growth curves. The growth functions considered were VB, Richards, Gompertz, 2-stage VB (Hearn and Polacheck 2003) and the VB with a logistic growth rate parameter. Laslett et al. (2002) proposed an alternative maximum likelihood for estimating growth curves from tag-recapture data based on estimating the joint density distribution of tag and recaptures lengths. They also proposed and developed a new growth curve that can accommodate a marked change in the growth pattern at some point in the life cycle. This model basically assumes two different growth Brody parameters (k_1, k_2) with a logistic function as transition between them; this is the von Bertalanffy with a logistic growth rate model (VB log k). Following Laslett et al. (2002) formulations, all growth function can be expressed as

$$l(a) = L_{\infty}f(a - a_0; \theta)$$

Where L_{∞} is the asymptotic length and f is a monotone increasing function with parameter set $\{a_0, \theta\}$ that equals 0 when $a = a_0$. The parameter a_0 can be interpreted as the theoretical age at which a fish would have had length 0 if it were to project its growth curve backwards. This parameters cannot be estimated from tag-recapture data, thus all age estimates are relative. To fully define the growth curve a_0 must be estimated from other sources. Eveson and Million (2008) parameterized these growth models as follows:

- VB: $\theta = \{k\}$ and $f(a - a_0; \theta) = 1 - \exp(-k(a - a_0))$
- Richards: $\theta = \{k, \alpha, \beta\}$ and $f(a - a_0; \theta) = (1 + \beta \exp(-k(a - a_0 - \alpha)))^{-1/\beta} - (1 + \beta \exp(k\alpha))^{-1/\beta}$
- 2 stage VB: $\theta = \{k_1, k_2, \alpha, \omega\}$ and $f(a - a_0; \theta) = \begin{cases} \gamma(1 - \exp(-k_1(a - a_0))) & \text{for } a \leq \alpha \\ 1 - \exp(-k_2(a - a_0 - \tau)) & \text{for } a > \alpha \end{cases}$
where $\tau = \alpha + \frac{1}{k_2} \log(1 - \gamma(1 - \exp(-k_1\alpha)))$
- VB log k : $\theta = \{k_1, k_2, \alpha, \beta\}$ and

$$f(a - a_0; \theta) = 1 - \exp(-k_2(a - a_0)) \times \left\{ \frac{1 + \exp(-\beta(a - a_0 - \alpha))}{1 + \exp(\alpha\beta)} \right\}^{-(k_2 - k_1)/\beta}$$

Note that the last term in the Richards function is included so that the function equals 0 when $a = a_0$. The 2 stage VB equation include two growth rates k_1, k_2 , and a τ term necessary to ensure smooth transition between the two curves at the change-point α . The VB log k growth curve represents a change from an initial growth rate k_1 to a growth rate k_2 , with a smooth transition between the two stages modeled by a logistic function. The parameter α determines the age at which the midpoint of the transition takes place, and β the rate of transition, as β is larger, the transition is sharper, larger values would result in the 2 stage VB function.

Before fitting growth models to the data, an exploratory analysis was performed to determine an appropriate functional form for the growth. Nominal average growth rates (cm/year) by fish were calculated by dividing the difference in size by the number of years at liberty and plotting against the average of its size at release (**Figures 4 and 5**). If the growth of yellowfin follows the standard VB it would be expected a linear relationship with negative slope as size increases.

The maximum likelihood fitting for the different growth models were done with three alternative algorithms available in R: i) The *grotag* function from the R package “fishmethods” (Nelson 2015), an implementation for maximum likelihood estimation of Fabens VB growth parameters as described by Francis (1988). This function allows estimating growth variability, outlier probabilities, measure error and seasonal effects on growth if applicable. ii) the R package “FSA” (Ogle 2016), with functions for estimating growth parameters for VB and Gompertz growth models with tag-recapture data, and iii) R code kindly provided by J.P. Eveson (Eveson et al 2015) that fit tag recapture data following the Laslett et al (2002) algorithms. All fitted models use non-linear fitting, requiring initial guess estimates for one or more parameters, these were taken from current growth estimates for Atlantic YFT and from the Indian Ocean when not available. The fits by the *grotag* function and

Eveson algorithms required also specification of lower and upper bounds for estimated parameters. Diagnostics and fitting solutions were evaluated based on statistical criteria such the log-likelihood and AIC (BIC) values and graphical plots of residuals.

4. Results and Discussion

Results and figures included only the YFT tag-recapture data considered appropriate for growth estimation as indicated in the data section. For releases the size distribution of tag YFT ranged from 30 to 137 cm FL with a median of 54 cm FL, the distribution is skewed towards smaller size fish, with 50% of fish between 46 and 64 cm FL. The recaptures show a similar distribution but displaced towards larger sizes, with a range from 11 to 190 cm FL and median of 63 cm FL. The 50% inter-quantile ranged from 53 to 92 cm FL. Of 486 observations, 404 recaptures indicated a positive growth of fish at liberty (83%). Negative size change was mostly observed in fish tagged from 40 to 60 cm FL and with a median of 60 days at large. The longest time at large was 7.15 years, but overall time at large shows a left-skewed distribution with a median of 118 days at large, and 75% of fish recovered in less than 1 year after release (319 days).

The scatter plot of nominal annual growth rates vs size at release (**Figure 4**) indicates an initial linear decline in growth rates of yellowfin between 30 and 55 cm FL, followed then by an increase between 55 and 70 cm FL, when it changes again to a linear decline of growth rates for fish over 70 cm FL. There is however a large variance of annual growth rates in particular for tagged fish larger than 60 cm FL (**Figure 5**). Overall the tag recapture data shows positive correlation between length increment and time at large for Atlantic yellowfin tuna (**Figure 6**).

The fit to the traditional VB growth model following Francis parameterization are shown in **Table 1** and **Figure 7**. AIC and log likelihood statistics indicated that the VB model including growth variability, measurement error, outlier probability and seasonal growth effects was the best fit to the YFT tag recapture data. Growth trajectory (**Figure 7**) and residual plots show that the simpler VB fail to capture all the variability observed. However parameter estimates of growth of asymptotic size were relative narrow (172 to 180 cm), but for estimates of growth rate k (0.21 to 0.29) the models favored values closer to 0.28. Estimated relative ages at release for tagged YFT were primarily ages 1, 2 and 3. Alternative parameterizations of the VB (Wang 1998) and a Gompertz model fit results are shown in **Table 2**. In this case, the VB parameters differed from the Francis' parameterization, with asymptotic size estimated about 230 cm and growth rates closer to 0.20. Although the same data was used, the statistics AIC and log likelihood were higher compared to Francis's models. The best fit was obtained with the Gompertz model, but in this case the estimated asymptotic size was 164 cm. Overall all fits show some trends in the residuals (**Figures 8** and **9**), with underestimation of increment of size for fish at large for short time, and some underestimation of the size increment for fish at liberty for longer periods. There is also a high negative correlation between estimated growth parameters, particularly for asymptotic size and growth rate k parameter (**Figure 10** left panel).

The parameters and fits to more complex models including the 2-stage and VB log K are presented in **Table 3**. These fits use a different algorithm for minimization (see details in Laslett et al 2002), negative log-likelihood values are similar to the AIC statistics of the previous models. Obtaining a reasonable solutions and convergence in all model formulations was very sensible to the initial guess inputs. Overall the best fit was given by the 2-stage growth model based on the lowest log likelihood. The VB log k , did not show an improvement compared to the VB in terms of likelihood. The estimated asymptotic size for the different models varied between 155 and 210 cm, in the case of the simple VB model, the estimate of $\mu(L_\infty)$ is lower than the other two approaches for estimation, only comparable with the Gompertz model. Similarly the estimates of the VB growth rate were higher (0.36) than the Francis or Wang VB estimates. Noticeable is the large estimated variance for measurement (σ_ϵ) indicating the large variability in the tag recapture data. The estimated mean age at release $\mu(A)$ ranged from 1.3 to 2.1 age relative of tagged fish, relatively younger / smaller fish if compared with the average age of released fish from prior models.

These preliminary results suggest that the 2 stanza growth model is appropriate for Atlantic YFT; at least as indicated from the nominal catch rates and fitting results of the 2 stanza models, with the "shift" of growth at about 50-60 cm FL, or equivalent relative age of 3.2. These results are similar to those obtained for the Indian Ocean YFT (Eveson et al 2015). However, contrary to the RTTP-IO results, the VB log k did fail to improve the fitting compared to the 2 stanza model, likely due to the large variability in the data. In the Atlantic YFT estimated variance at tagging is twice the RTTP-IO, albeit the sample size in the RTTP-IO is roughly 10 times larger than the tag recapture data for Atlantic YFT ($n = 486$).

However, there is still controversy whether the 2 stanza growth is a biological feature or rather a size selectivity effect on the sampling for tag recapture information (Eveson and Million 2008, Chassot et al 2008, Kolody 2011). In the case of Atlantic YFT the advantage of our data is that includes releases and recaptures from several fishing gears and not only purse-seine as in the case of the RTTP-IO. This is also shown in the size frequency distributions of both releases and recaptures. The Atlantic YFT tag recapture data covers larger sizes of fish and also larger times at large. Another important consideration is the wider spatial and temporal distributions of tag recaptures for the Atlantic YFT, although it is still important to obtain tag recapture data from the southern Atlantic region, particularly from off the South American coast.

For Atlantic YFT there is wide range of estimated asymptotic size, however as indicated by Francis (1988) is important to keep in mind that comparison of growth parameters are not valid when estimated from direct ageing versus tag recapture data (Francis 1988), or cohort size length frequency analysis if not bias corrections are made and appropriated parameterizations are used for estimation. Unfortunately, this is the situation for current growth models of Atlantic YFT; Shuford et al (2007) and Lessa and Duarte-Neto (2004) estimates are based on otolith and fin-spine readings and their results indicated an asymptotic size about 230 - 257 cm, more comparable with the estimates obtained in this document with the VB model (237 cm) using the Wang parameterizations that bias corrected asymptotic size estimates from the tag recapture data. In the case for estimates of Brody growth rates; from ageing data growth rates are estimated around 0.27 to 0.28, instead from the tag recapture data there is large variability on growth rates as function of the curve fitted, for example VB models suggest growth rates at about 0.20 with Wang's parameterizations and 0.28 with Francis's parameterizations. In the case of 2 stanza growth rates, they were estimated much higher in both phases of growth, above 0.38. A limitation of growth estimates based on tag recapture data is that actual age is unknown, but depends on the assumption of t_0 (e.g. a_0). The 2 stanza growth models evaluated both estimate a mean age at release and a variance associated, but it requires assuming a given distribution, in these analyses it was assumed a log-normal distribution, similar to Leslett et al (2002) or Eveson et al (2015). Leslett (2002, 2004) indicated robustness of the fitting to the assumed age at released distribution, however it is unclear if the case of multimodal size/age tagging releases the model is robust, and further simulation studies should confirm this.

In summary, tag recapture data for Atlantic YFT provided preliminary estimates of growth parameters although large variability of individual growth (likely due to uncertainty in reporting) prevented for getting robust estimates. As with the Indian Ocean, Atlantic YFT appears to show a 2 stanza growth process. Large sample and quality of tag recapture data should improve the analyses, but must be noted and taking into account other larger tagging programs, wider coverage both in size and geographic distribution is important, particularly maintaining a multi-gear release and recovery effort as this minimize the effects of selectivity in the analysis. However, beyond this is clear that approaches that integrated multi sources of growth information should be investigating for Atlantic YFT, in similar fashion as it has been done for the Indian Ocean (Dortel et al 2015). This approach can already be explore for YFT as ageing, size frequency and tagging data are already available from several studies in the Atlantic.

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Table 1. Fitting results YFT tag recapture data and estimated von Bertalanffy growth parameters following Francis (1998) parameterization. In Francis's parameterization for tag recapture data the three usual VB parameters are replaced by g_a , g_b that are the mean annual growth increments of fish of arbitrary reference lengths a and b , lengths well represented in the tag release data. From the base VB model parameters for growth variability (nu), outlier's probability (p), measurement error (m) and seasonal growth (u , w), were sequentially included and estimated.

Model Parameters	VB + growth var		VB + outlier p		VB + measure error		VB + seasonal		
	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE	
Mean growth rates	ga	27.07	1.6	33.19	2.5	32.56	2.52	32.11	2.29
Mean growth rates	gb	6.89	2.27	6.89	2.41	6.89	2.46	6.89	2.77
Seasonal variation	u	0	0	0	0	0	0	0.69	0.101
	w	0	0	0	0	0	0	0.947	0.017
Growth variability	nu	0.904	0.079	0.725	0.072	0.671	0.062	0.683	0.059
Measurement error	s	4.181	0.525	4.239	0.535	3.893	0.516	2.654	0.507
	m	0	0	-1.888	0.614	-1.826	0.564	-1.11	0.479
Outliers	p	0	0	0	0	0.025	0.018	0.06	0.017
-Log likelihood		1831.5		1826.4		1820		1800.3	
AIC		3671		3662.8		3651.9		3616.7	
VB pars Francis									
$Linf$		180.856		172.513		173.187		173.693	
K		0.21343		0.288308		0.280347		0.274659	

Table 2. Fitting results YFT tag recapture data and estimated growth parameters of three VB Fabens model following Wang (1998) parameterizations and Gompertz curve. L_1 and L_2 denote lengths at release and recapture, respectively. \bar{L}_2 mean length at release, Δt time at liberty in year units.

Model parameterization	Parameters estimates			AIC	log likelihood	df
Wang 1	$Linf$	K	b			
$E(L_2 - L_1) = (L_\infty + \beta(L_1 - \bar{L}_1) - L_1)(1 - \exp(-k\Delta t))$	215.989	0.203583	-0.36193	3939.21	-1965.6	4
Wang 2	a	K	b			
$E(L_2 - L_1) = (\alpha + \beta L_1)(1 - \exp(-k\Delta t))$	237.2315	0.20358	-1.36195	3939.21	-1965.6	4
Wang 3	a	K	b			
$E(L_2) = L_1 + (\alpha + \beta L_1)(1 - \exp(-k\Delta t))$	237.2313	0.20358	-1.36194	3939.21	-1965.6	4
Gompertz	$Linf$	g_i				
$E(L_2) = L_\infty(L_1/L_\infty)(\exp(-g_i\Delta t))$	163.967	0.521304		3924.69	-1959.35	3

Table 3. Fitting results YFT tag recapture data and estimated growth parameters of four growth curves following Laslett et al (2002) parameterizations for the VB, Richards, 2 stage (LEP) and VB log k models. All models assumed a logarithm distribution of age at release $\mu(A)$ and normal distribution of asymptotic size $\mu(L_\infty)$.

Model	$-\text{LogLik}$	$\mu(L_\infty)$	$\sigma(L_\infty)$	k_1	k_2	α	β	ω	$\mu(A)$	$\sigma(A)$	σ_s
VB	3993.791	155.154	31.02863	0.36008					0.238917	0.29372	7.557068
Richards	3989.494	209.977	37.55558	0.6		1.42795	0.88492		0.602133	0.229284	7.878836
2-Stage	3986.868	180.000	10.00917	0.384813	0.43211	3.189032		0.448588	1.032857	0.226003	5.09162
VB log K	3993.791	155.162	31.02938	0.360041	0.073558	14.59013	15.11485		0.238957	0.293714	7.557129

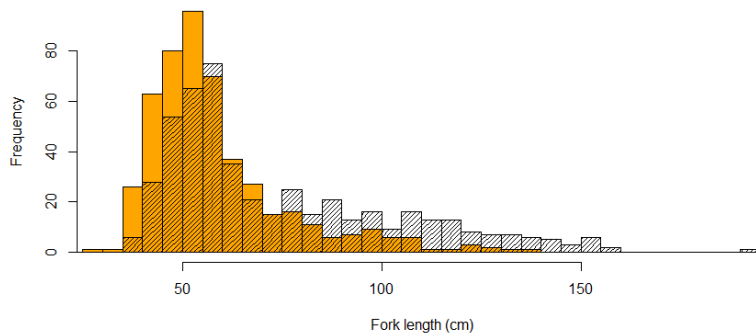


Figure 1. YFT tag recapture data size distribution of release fish (solid color bars) and recaptures (shaded bars).

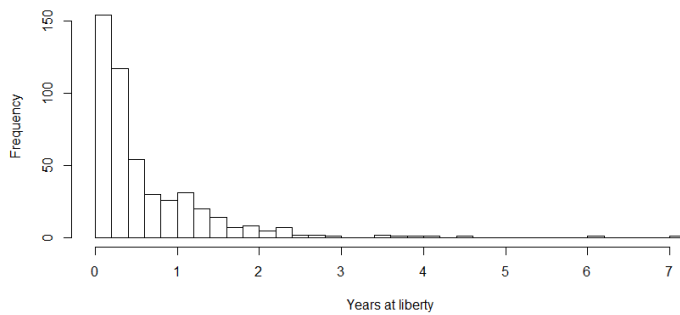


Figure 2 Frequency distribution of time at large for Atlantic YFT tag recapture data.

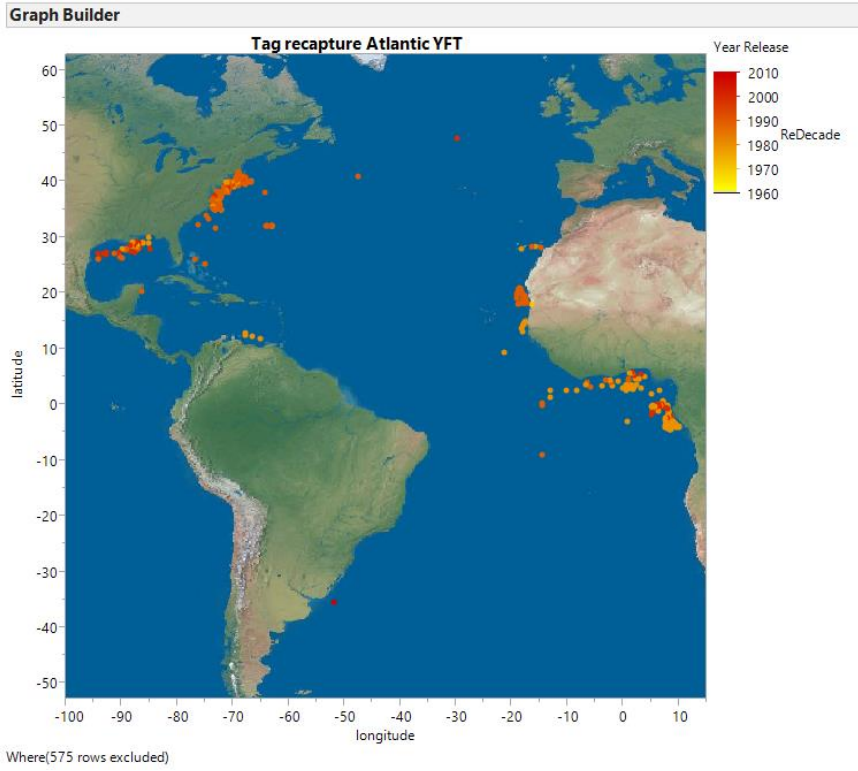


Figure 3. Spatial distribution of YFT tag releases.

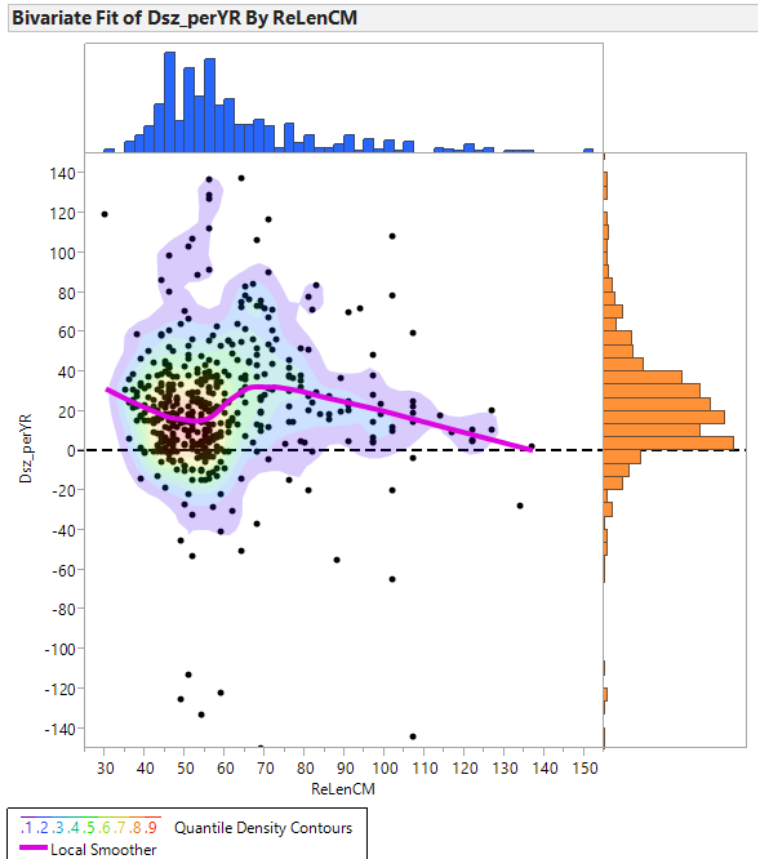


Figure 4. Scatter plot of the nominal growth rates (cm/year) vs the size at release for Atlantic YFT. The contours show the density of observations and the solid line a local smoother of the data trend.

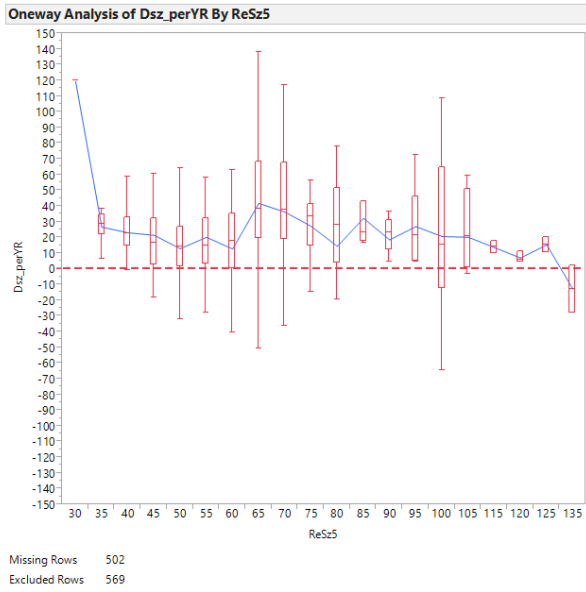


Figure 5. Boxplots of the nominal growth rates (cm/year) by 5 cm bin size at release intervals for Atlantic YFT.

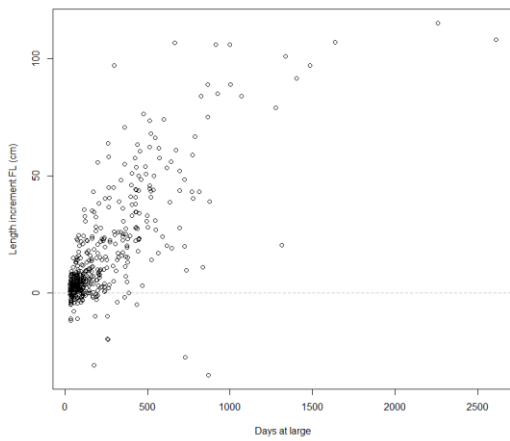


Figure 6. Scatter plot of size increment vs time at large (years) for YFT tag recapture data.

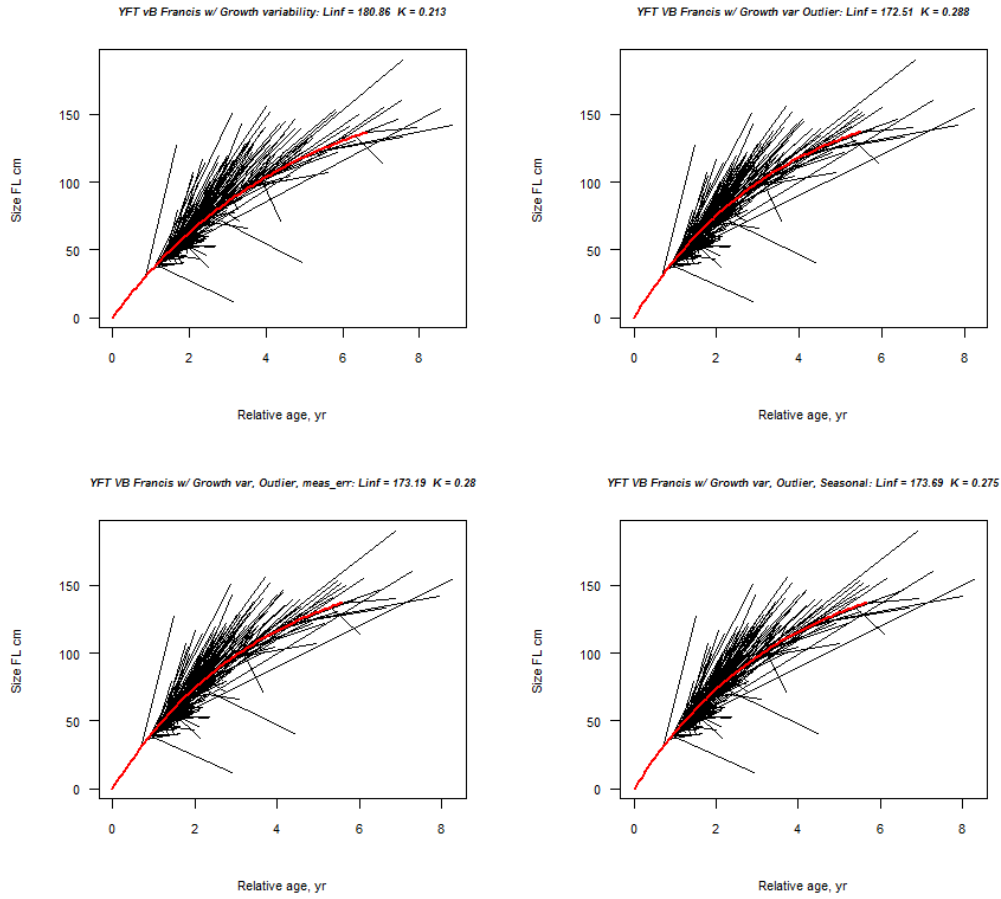


Figure 7. Growth trajectories of YFT tag recaptures and estimated growth VB curve for four VB models following Francis parameterization, the different fits correspond to models that sequentially included: growth variability (top-left), outlier probability (top-right), measurement error (bottom-left) and seasonal effects (bottom-right).

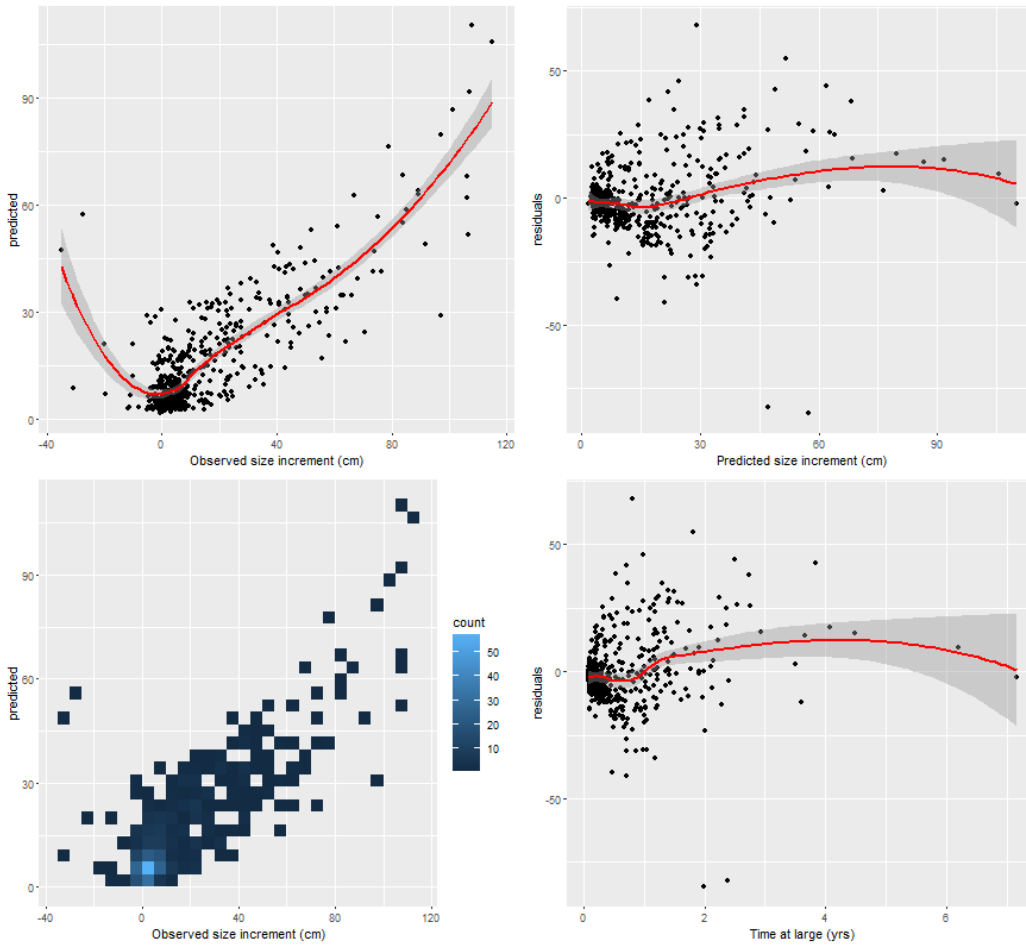


Figure 8. Typical diagnostic plots for the YFT tag recapture fit with the VB Wang parameterization model(s). Left column shows the observed vs predicted size increments with smoother trend of the data, bottom plots shows the density of observations per 5 bin size. Right column shows the residuals vs the predicted size increment (top) of the time at large (bottom).

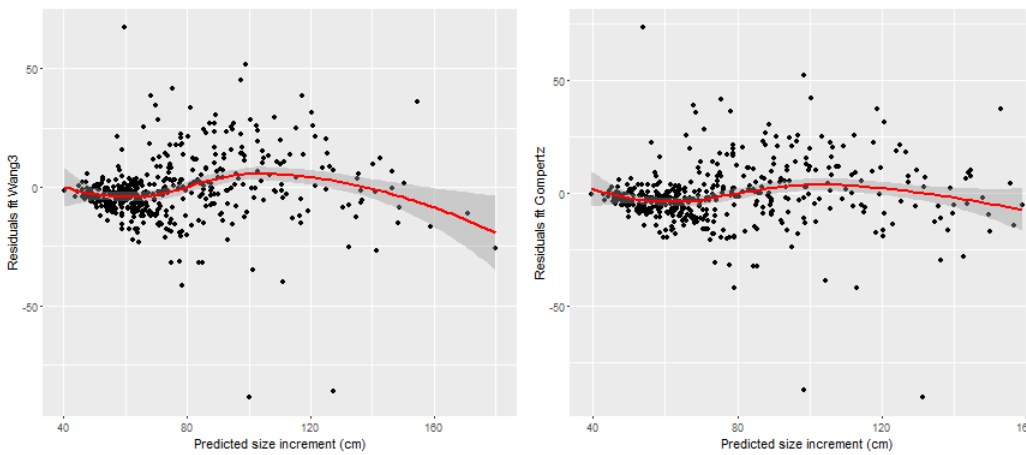


Figure 9. Plot of residual for the VB Wang parameterization (left) and Gompertz models (right) with smoother trend of the data.

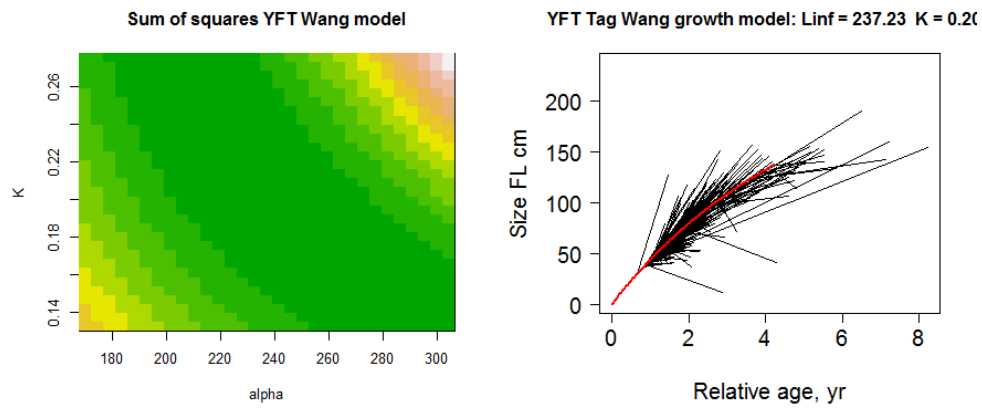


Figure 10. Contour plot of the sum of squares for values of alpha and K parameters (left) and predicted growth trajectory for the fitted VB Wang 3 parameterization model (left).