Two simple alternative growth models for skipjack tuna (*Katsuwonus pelamis*) in the Indian Ocean, as estimated from tagging data.

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Abstract

Preliminary tagging data from the Regional Tuna Tagging Project – Indian Ocean were used to calculate updated growth parameters for skipjack tuna (*Katsuwonus pelamis*) in the Indian Ocean. The parameters were calculated using two variations of Fabens method and a Schnute model. The L_{∞} values estimated by the two Fabens methods are within historical values calculated for skipjack in the Indian Ocean, while the K values were lower, implying a slower growth rate than historically assumed. The Schnute model indicated that growth is different between small and large individuals. None of the model fits were particularly good, although this is probably due to the very preliminary nature of the data. Akaike information Criterion values were calculated for the different models and the Fabens model assuming a power law relationship between growth variability and time at liberty had the lowest AIC value. It is hoped that the models estimated in this study can be compared to more flexible and complex two-stanza growth models to ascertain whether the simple models are appropriate for use in future skipjack stock assessment models and hence for management advice.

1 Introduction

Growth is one of the four factors (recruitment, growth, natural mortality, and fishing mortality) of biomass change, and it is therefore a critical requirement for assessing the status of an exploited population. Estimates of growth, or more specifically a mathematical description of increase in length or weight with age of fish, are essential for stock assessment methods such as cohort analysis (Ricker 1975) or age-structured models (Hillborn 1990). Different methods are commonly used to obtain growth estimates: (1) analysis of growth increment data from tagging studies (Fabens 1965, Francis 1988), (2) analysis of the hard parts of the fish (e.g., otoliths, vertebrae, etc; Campana 2001), and (3) analysis of cohort progressions in length-frequency distributions (Schaefer 1961).

Unfortunately, skipjack (*Katsuwonis pelamis*) has proved difficult to age as the modes in length-frequency data are difficult to identify because of high growth rates, continuous recruitment, and variability in growth (Schaefer 1961, Joseph and Calkins 1969) and direct estimates of age have been hampered by the lack of consistent check marks on hard parts of the fish (Wild and Forman 1980, Uchiyama and Struhsaker 1981). Furthermore, skipjack growth parameters may vary with latitude (Bard and Antoine 1986). Due to these difficulties, Josse *et al.* (1979) suggested that tagging data provide the best means of estimating growth rates for skipjack. In the Indian Ocean region, the recent availability of data from the Regional Tuna Tagging Project of the Indian Ocean (RTTP-IO) may enable scientists to assess the growth of skipjack in the Indian Ocean with tagging data. Although this has been done before (Adam 1999), the work was restricted to the Maldives.

The aim of this paper is to provide two different growth models, fitted to the preliminary tagging data available for skipjack tuna in the Indian Ocean. It is hoped that these models can be contrasted with more dynamic two-stanza models (Fontaneau pers com.) in order to obtain a “more realistic” model for inclusion in stock assessment models and hence for management advice.

2 Models

The data included in this analysis are the skipjack tagging data available to the IOTC Working Party on Tagging Data Analysis (WPTDA) from the RTTP-IO. Due to the fact that the data currently available from the RTTP-IO are preliminary and require “cleaning up”, for the purpose of this study, no error in the measurement of length was simulated. This is clearly an oversimplification and can be considered unrealistic (Francis 1988), but measurement error can be simply incorporated into these models at a later stage once the available tagging data has been finalised.

2.1 Fabens estimation

Fabens (1965) formalised the translation of the Von Bertalanffy curve (1938) into a form suitable for use with tagging data. This model was chosen in preference to other methods such as those formulated by Gulland and Holt (1959) and Munro (1982) as it is considered to produce more accurate estimates of L and K (Sundberg 1984). The model is described by the following equation:

$$\Delta L = (L_\infty - L_t)(1 - e^{-K\Delta t})$$

Where: ΔL is the difference between the length at release and the length at recapture.
L_∞ is the asymptotic average maximum body length
L_t is the length at release
K is the growth rate coefficient, and
Δt is the time at liberty.

Two different assumptions were simulated regarding the variation in growth among the observed data. Firstly, a constant variance was assumed where the variance was independent of the observed length. This model was fitted by minimising the following negative log likelihood:

$$-veLL = -\sum \ln\left(\frac{1}{\sqrt{2\pi}\sigma} e^{\frac{(\Delta L - \Delta\hat{L})^2}{2\sigma^2}}\right)$$

Where: σ^2 is the constant variance of the residuals fitted as an additional parameter. This assumption will be referred to as the Fabens method constant variation model in this paper.

Francis (1988), however, suggested that several other deviation patterns could occur. In this study, a residual standard deviation that followed a power law was simulated. This was decided on after preliminary attempts to fit the data using lognormal and constant multiplier variances were unsuccessful. The residual standard deviation was thus:

$$\sigma = \upsilon \Delta \hat{L}^{\tau}$$

Where: υ and τ are additional parameters estimated separately.
This assumption will be referred to as the Fabens method power law model in this paper.

2.2 Schnute model

Although the Von Bertalanffy model is commonly used in fisheries stock assessments, it is not necessarily the best or most realistic model in every scenario (Haddon 2001). Baker *et al.* (1991) proposed a length-based analog of Schnute's (1981) size-at-age model. This length-based growth model related mean size at recapture to mean size at release. Francis (1995) reformulated Baker *et al.'s* model to (1) make the parameters more meaningful, (2) optimize the model for parameter estimation, and (3) allow the error structure to be formulated in terms of growth increments, rather than lengths at recapture. The model equation includes five parameters; the first two, y_1 and y_2 are arbitrary fish sizes, small and large respectively, fixed by the user; the remaining 3 which are estimated, are g_1 and g_2 which are the mean growth increments for fish of size y_1 and y_2, respectively, over a given time period (years in the following analysis); and b, which describes the curvature in the model. A further four parameters, a, c, λ_1 and λ_2 are estimated within the model and are simply formulated from the above parameters to make the final model calculation more convenient.

The formulation of the model when a $\neq 0$ and b $\neq$ 0 is given below (Francis 1995). This model is referred to as the Schnute growth model (Maunder 2001):

$$G_{pred} = -L + \left[L^b e^{-a\Delta t} + c\left(1 - e^{-a\Delta t}\right)\right]^{\frac{1}{b}} \qquad a \neq 0,\ b \neq 0$$

Where: G_{pred} = predicted mean increment of growth
L = length at release
Δt = time at liberty, and
a, c, λ_1 and λ_2 are parameters used to make the calculations more convenient.

These are defined as

$$a = \ln\left[\frac{y_2^b - y_1^b}{\lambda_2^b - \lambda_1^b}\right]$$

$$c = \frac{\left(y_2^b \lambda_1^b - y_1^b \lambda_2^b\right)}{\left(\lambda_1^b - y_1^b + y_2^b - \lambda_2^b\right)}$$

$$\lambda_1 = y_1 + g_1$$
$$\lambda_2 = y_2 + g_2$$

Variance in growth is defined as a function of both length at release and time at liberty, and this model is referred to as the *Generalized variance model* (Maunder 2001):

$$\sigma_g^2(L,\Delta t) = \alpha L^{\beta} \Delta t^{\gamma}$$

To avoid computational problems the following formulation is used:

$$\sigma_g^2(L,\Delta t) = \exp(\ln(\alpha) + \beta \ln(L) + \gamma \ln(\Delta t))$$

The growth increment reduces with increasing length at release and increases with time at liberty; therefore, following the Francis variance model, β and γ are expected to be negative and positive, respectively. If both β and γ are equal to zero then the variance is constant, if β is zero then the variance is a function of time at liberty only, and if γis zero then the variance is a function of length at release only.

As measurement error has been ignored, the negative log likelihood term for this model follows Fournier *et al*.s (1990) robust likelihood function:

$$-\ell(\theta | L, L', \Delta t) = -\frac{1}{\sqrt{2\pi(\sigma_g^2)}} \exp\left(-\frac{(G_{obs} - G_{pred})^2}{2(\sigma_g^2)}\right) + 0.01$$

The addition of the 0.01 ensures that the influence of observations reduces rapidly as their distance from the predicted value grows greater than three standard deviations (Fournier *et al* 1990).

2.3 Model selection

The different models were evaluated using the Akaike Information Criterion (AIC; Akaike 1973).

$$AIC = -2 \ln \ell + 2p$$

Where: $\ln \ell$ is the log likelihood, and
p is the number of parameters

The best model is that with the lowest AIC value depending on the criteria preferred.

3 Results

3.1 Fabens method

The output parameters for the Fabens method models are presented in Table 1. The model assuming a power law relationship for growth variance provided marginally better fits to the observed data according to the estimated log likelihood values. It does, however, necessitate the estimation of an additional parameter. The L_∞ values differed between models with the constant variance model estimating a smaller L_∞ value. The K values are very similar, with the constant variance model estimating a slightly higher growth rate than the power law model.

Table 1: Parameter estimates for the growth of skipjack tuna using Fabens Method.

Parameter	L_∞	K	σ^2	υ	τ	R^2	$-\ln \ell$
Constant variance	79.55	0.27	2.33	NA	NA	0.49	19818.88
Power law variance	82.91	0.24	NA	1.87	0.17	0.49	19594.55

The model fits of growth to the observed growth data are presented in figures 1 and 2 for the constant variation and power law models respectively. There is a high degree of variation in the observed growth rates. Some of the variation may be reduced once the preliminary dataset has been finalised, so it is difficult at this stage to infer any conclusion from the observed data. This has resulted in relatively poor model fits to the data. The R^2 values indicate that the two models are effectively explaining the same amount of variation in the data. Both models estimated a similar rate of growth per year, a characteristic already observed by the similar K values estimated for both models.

The relationship between growth variability and time at liberty is presented in figure 3 for the power law model. The model estimates a logarithmic relationship between growth variability and time at liberty. Variability is estimated to increase rapidly in the first six month after release, after which the rate of variability decreases. No true asymptote is reached, however, the variance in growth is relatively similar after one year.

3.2 Schnute model

The parameter estimates for the Schnute model are presented in table 2. As with the Fabens method, the fit of the model was not good. The growth parameters g_1 and g_2 clearly indicate that growth is not constant amongst all size groups with growth rate decreasing with increasing length.

Table 2: Parameter estimates for the Schnute growth model

Parameter	g_1	g_2	b	α	β	γ	R^2	$-\ln \ell$
Value	8.15	5.97	6.90	3.15	-0.05	0.18	0.50	19643.24

The Schnute model fit to the observed data is presented in figure 4. The fit of the Schnute model to the data, differs to both Fabens Method estimations. The Schnute model estimates higher growth rates for all fish sizes, but particularly for smaller fish that lie outside the range of the observed data. Unlike the two Fabens method estimations, the growth rate predicted by the Schnute model does not continue to decrease with size, but rather stabilises for skipjack greater than 50 cm in length. This model explained marginally more of the variation in the data than the Fabens estimations according to the calculated R^2 value.

The variance in the growth rate as a function of time at liberty for the Schnute model is presented in figure 5. This relationship estimated by the Schnute model is very similar to that estimated by the Fabens power law model. Both models predict a logarithmic relationship between growth variation and time at liberty, with the majority of variation occurring in the first six months after release with a more gentle increase occurring after one year at liberty.

3.3 Model selection

The AIC values calculated for the different model scenarios are listed in table 3. Similar to the negative log likelihood values, the Fabens power law model showed the lowest AIC value from all models, which, in turn, can be interpreted as the best model for describing the growth characteristics of skipjack in the Indian Ocean. It must be noted, however that the data used in these models are very preliminary and the differences in the values of the goodness of fit between models, small. It is thus clear, that further analysis should be carried out before making any definitive conclusions.

Table 3: AIC values for the different growth models calculated using skipjack tagging data

	Number of parameters (p)	$-\ln \ell$	AIC value
Fabens method (constant variation)	3	19818.88	39643.76
Fabens method (power law variation)	4	19594.55	39197,10
Schnute model	6	19643.24	39296,48

4 Discussion

In the absence of reliable growth estimates for skipjack tuna from direct age estimation and/or length-frequency analysis, mathematical descriptions of growth from tagging data, i.e. growth increment and time at liberty provide the best alternative method for growth estimation (Adam 1999). A number of studies have reviewed the growth rates of skipjack tuna and have described a wide range of estimates for the various growth parameters (Rothschild 1967, Joseph and Calkins 1969, Josse *et al.* 1979, Forsbergh 1980, Bayliff 1988). This study has utilised two different models for estimating the growth of skipjack tuna in the Indian Ocean. The commonly used Fabens Method produces estimates of the standard Von Bertalanffy growth parameters (excluding t_0) thus making comparisons between studies possible.

The L_∞ values estimated by both Fabens models in this study lie within the range of values historically calculated for the Indian Ocean, which range from a maximum of 90 cm (Mohan and Kunhikoya 1985) to a minimum of 60.6 cm (Marcille and Stequert 1976). The K values estimated by the models in this study are very similar. Although the K values estimated in this study are similar to the value calculated by Hallier and Gaertner (2006) in the Atlantic Ocean they are both lower than any other K values calculated for this species in the Indian Ocean (Marcille and Stequert 1976, Mohan and Kunhikoya 1985, Adam 1999). The higher values of L_∞ estimated in this and other studies are probably more realistic taking into account fishery catch at length data. Apart from the study by Adam (1999), most growth studies of skipjack tuna from the Indian Ocean are from length-frequency data. For skipjack tuna, a tropical species exhibiting year-round spawning (Stéquert and Ramcharrun 1996), growth estimates using length-frequency methods are considered to be of little value (Joseph and Calkins 1969, Josse *et al.* 1979, Wild and Hampton 1994) and therefore those results may not be strictly comparable with the results of this analysis.

Previous growth studies in the Indian Ocean which have utilised tag and recapture data have been concentrated around the Maldives archipelago (Yesaki and Waheed 1992, Anderson *et al.* 1996, Adam 1999) two of which produced linear estimates of growth (Yesaki and Waheed 1992; Anderson *et al.* 1996) which are considered inappropriate for describing the growth of tuna species across their full size range (Sibert *et al.* 1983). The Von Bertalanffy growth parameters estimated by Adam (1999) were considerably different to those obtained in this study. The L_∞ and K values in that study being 64.3 cm and 0.55 y^{-1} respectively. Adam's (1999) study, however was based on data collected solely from skipjack tagged and recovered in the Maldives, included 216 data points as opposed to the 8755 included in this study and estimated an L_∞ that is not really supported by fishery data.

The common usage of the Von Bertalanffy growth model does not necessarily mean that the Von Bertalanffy approach is the most suitable for describing the growth of skipjack tuna. As a result an additional method, the Schnute model, was included in this study. Direct comparisons of this method with the other growth studies are not as straightforward, as the Schnute model does not produce estimates of the Von Bertalanffy parameters except in the special case where the parameter b is set to one (Maunder 2001) which did not occur in this study. The Schnute model is more flexible than the Fabens method, with the inclusion of extra parameters facilitating a wider range of relational forms than the standard Von Bertalanffy model (Haddon 2001). This method has been used to investigate the growth of skipjack in the eastern Pacific Ocean (Maunder 2001). In both the Pacific and Indian Ocean, growth was found to decrease with increasing size with estimates of rapid growth for smaller individuals and fairly constant growth for medium to large individuals. Unfortunately, the range of release lengths does not include significant numbers of small and large fish, making the estimation of growth less certain for these sizes. Although the Schnute model describes the data better than the simple constant variation Fabens method model, it does not fit the data as well as the power law model although it does have the best R^2 value. The additional parameters estimated by the model resulted in a higher AIC value than the power law model. It is possible that the inclusion of measurement error will change the fit of the model, but due to the very preliminary nature of the data it was decided to keep the model simple, as the final data may differ from those currently available. At a later stage, the model can be re-parameterised and re-estimated.

The purpose of this study has been to provide updated estimates of growth for skipjack tuna in the Indian Ocean, using the recently acquired data from the RTTP-IO. It is of increasing concern, however, that most mathematical models used to simulate growth studies in fishes do not take into account changes in growth patterns that occur between life stages (Dumas *et al.* 2007). For this reason, more complex, two stanza growth models have been proposed to fully incorporate these changes (Gasceul *et al.* 1992). Two stanza growth has been observed and modelled for several tuna species using both tagging and otolith studies (FAO 2001). The models devised in this study have intentionally been made very simple. It is envisioned that the growth models proposed in this study can be contrasted with the more complex models in order to determine if they are still appropriate for simulating the growth of skipjack tuna in the Indian Ocean. It would also be useful to assess the influence the different models have on potential skipjack assessment models, as stock assessment models provide the bulk of information used for fisheries management advice.

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Appendix

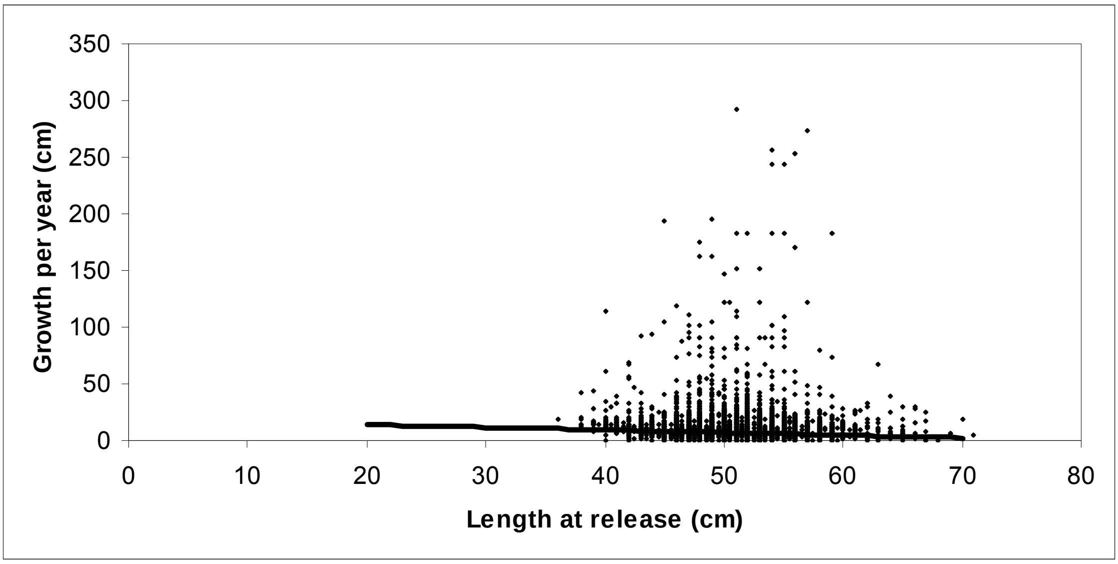

Figure 1: Fit of the Fabens method growth model to the observed tagging data for Skipjack tuna in the Indian Ocean using constant variance in growth.

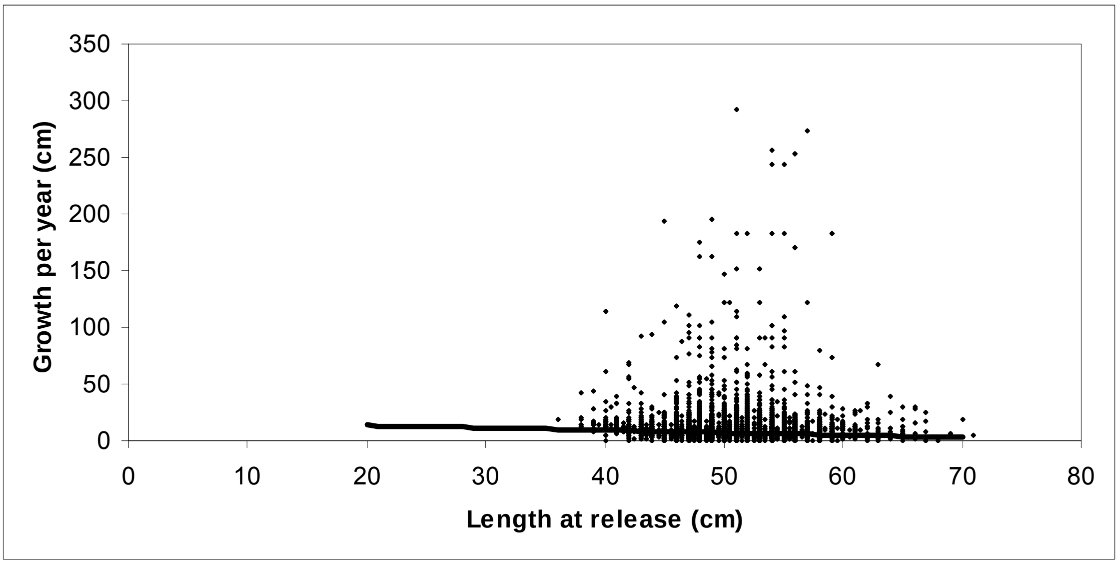

Figure 2: Fit of the Fabens method growth model to the observed tagging data for Skipjack tuna in the Indian Ocean using a power law of growth variance.

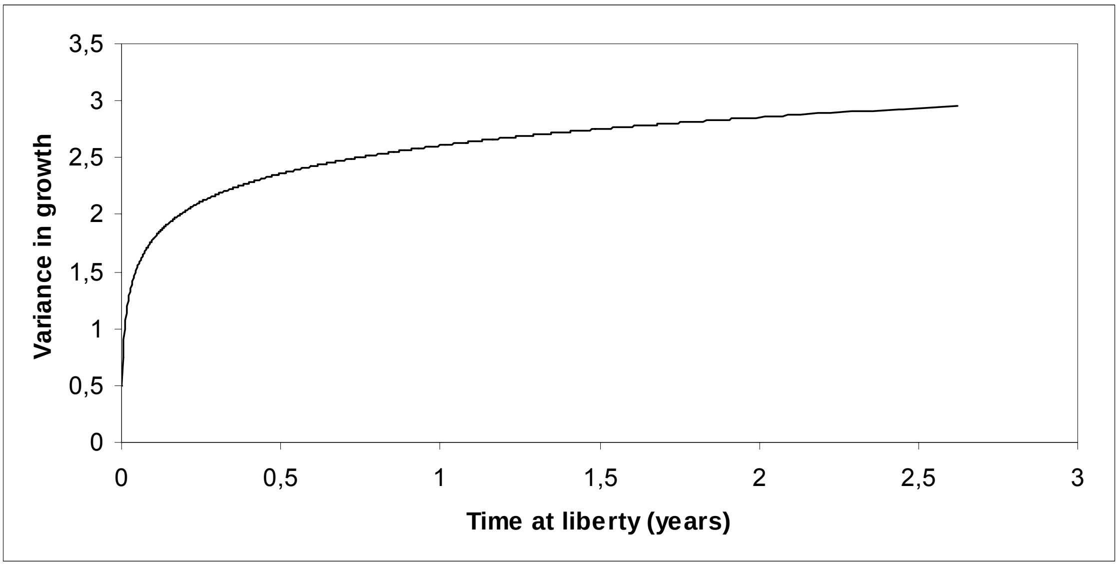

Figure 3: Individual growth variation versus time at liberty for the Fabens method growth model

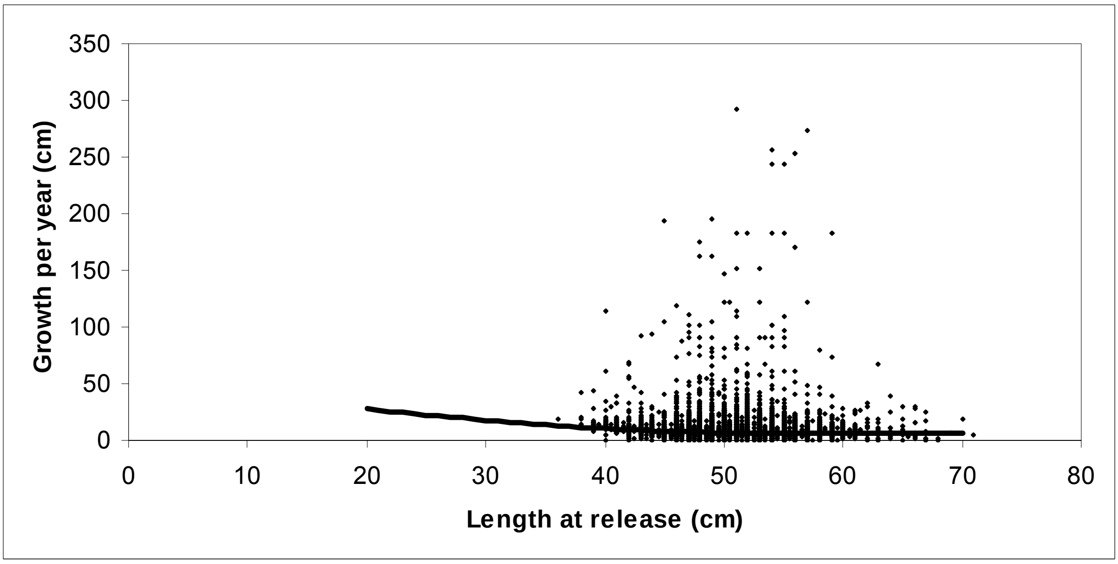

Figure 4: Fit of the Schnute model growth model to the observed tagging data for Skipjack tuna in the Indian Ocean.