***Fitting mark recapture data collected on Pristipomoides filamentosus in the Main Hawaiian Islands to determine otolith independent growth estimates.***

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***Abstract***

*Pristipomoides filamentosus* is an important species in the Hawaiian archipelago, accounting for a large percentage of the catch for the commercial fishery targeting deep-water bottomfish. With a single exception targeting juveniles, all work to quantify growth in this species in the region has relied on otoliths to estimate the age of individuals. In the late 1980s, the State of Hawaii’s Division of Aquatic Resources performed a mark recapture study on the species measuring and tagging 4,172 fish. Over the next decade, state researchers and local fishermen recaptured and obtained measurements for more than 10% of all marked fish. Fit to Fabens’ parameterization of the von Bertalanffy growth function, we estimate the Brody growth coefficient and maximum length at age for the species, independent of otolith age estimates, and compare our results to prior estimates for the species. We obtained parameter estimates using a maximum likelihood and four error structures and then compared these results to those obtained using non-linear least squares and Bayesian approaches. Parameters estimates obtained in this study provide support for using growth models fit using otolith striation to age individuals (Ralston and Miyamoto, 1993) and estimates obtained using a bomb radiocarbon validated aging approach (Andrews et al. 2017).

***Introduction***

*Fishery Background*

*Pristipomoides filamentosus* is a species of long lived snapper distributed throughout the tropical Pacific and Indian Oceans from east Africa to Hawaii and Tahiti, southern Japan to Northern Australia (Allen, 1985; Andrews et al., 2012). In Hawaii, *P. filamentosus* constitutes a significant fraction of the catch of the deep-water bottomfish fishery [Kimberlee Harding DLNR/PIFSC-JIMAR]. The fishery uses hook-and-line gear to land *P. filamentosus* in addition to a number of other species of snappers, jacks, ulua, and one endemic grouper species. During the 2016-2017 federal bottom fish fishing year, 338 commercial fishers landed 234,299 lbs of Deep 7 bottomfish during 2,307 trips. Of these landings, *Pristipomoides filamentosus* was the most represented species, accounting for 59% of the catch by pieces reported and accounting for approximately 58% of the fishery’s annual value of $1,646,044 [Kimberlee Harding DLNR/PIFSC-JIMAR Report Email from Uncle Roy (RNVFISHING)]. Due to the importance of the fishery, both economic and cultural, a number of studies have expended a great amount of effort since the early 1980’s to better understand aspects of the biology and ecology of the species.

*History of Age Growth Estimation*

A number of these studies have focused on estimating growth parameters for *P. filamentosus* fit using the von Bertanaffy function (VBGF) to estimate the relationship between an individual’s size and age. The traditional VBGF fits an asymptotic curve using the parameters and K using the following formula:

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Where is the length of an individual at time t and is a function of the Brody growth rate and the , the asymptotic length at which growth is zero. The parameter accounts for the initial size of the species initial size of the species.

In the Hawaiian archipelago, studies fitting the VBGF for *P. filamentosus* have primarily relied on otolith structure and composition to estimate individual age (Ralston & Miyamoto, 1983; Uchiyama & Tagami, 1984; Radtke, 1987; Demartini, Landgraf & Ralston, 1994; Moffitt & Parrish, 1996; Andrews et al., 2011, 2012). Like many fish species, the otolith structure of *P. filamentosus* is deposited in thin layers throughout the individual’s life, producing a pattern of banded concentric rings when sectioned. Counting the number of increments and/or integrating otolith width has been previously used as a proxy for the age of an individuals. However, determining the age of mature *P. filamentosus* by counting otolith rings is problematic as otolith growth in mature individuals may be episodic, rather than continuous, with poorly defined growth rings, leading to underestimation of age for mature individuals and an overestimation of growth rate (Ralston & Miyamoto, 1983). In 2011 and 2012, Andrew’s et al. published results comparing the radiochemical composition of otoliths using lead-radium and bomb radiocarbon dating to estimate individual ages. Their results showed concerns surrounding episodic growth of otoliths was warranted and that previous studies reporting fast growth rates and short lifespans were not accurate. Their results indicate individual longevity twice that previously reported. While discussing their results, Andrews et al, indicated that growth estimates from mark-recapture data should be included in further refinements of growth rate parameters.

*Mark-recapture Estimation of VBGF Parameters*

Quantitative methods for determining growth curve parameters from mark-recapture data have been developed since the mid 1960s (Fabens, 1965). Rather than fitting a growth curve to a series of measured lengths and known or estimated ages, the methods manipulate the VBGF into the following form:

Which relies on the observed length when an individual is first marked (, and again when it is recaptured , to determine the growth of the fish during the period between marking and recapture events (Fabens, 1965). Parameters and are then estimated. Because the model structure does not require the age of individuals to be known, the method is often used when it is difficult to accurately age an individual. For *P. filamentosus* in the MHI, such an approach is useful to validate previous estimates of growth independent from otolith based age estimates.

The method, as initially proposed, assumes that individual growth strictly adheres to the growth parameters for the population and a constant variability in modeled residual error across all size classes. However, it is well known that individual variability in growth can often vary based on sex, time of year, food availability, the temperature, salinity, disease, genetic factors, etc. Furthermore, as initial capture size increases, the change in size for individuals recaptured declines as does the residual error. Additionally, measurement error can bias growth parameter estimation. A number of modifications to Fabens’ method have been developed to address these shortcomings by allowing each individual to deviate from the overall population. Francis (1988) proposed a maximum likelihood approach to fitting population growth curve parameters from individual growth measurements. Wang (1998) expanded on this approach including an additional model parameter, , explicitly accounting for the deviation of individuals from the overall population. When this parameter is restricted to zero, Wang’s approach becomes functionally equivalent to that of Francis (Wang, 1998).

The goal of this manuscript is to determine growth rates parameters from a mark recapture dataset from *P. filamentosus* in the Main Hawaiian Islands using improved Fabens’ models and compare them to previous estimates for the species that were made using otolith age estimates. This work differs from the work that came before it in that it does not rely on age estimates from otoliths, spans a range of sizes for the species, and has a sample size of individuals only exceeded by the 1996 Moffitt and Parrish study using ELFAN to measure growth, with samples derived entirely from within the Main Hawaiian Islands. We also hope to assess the validity of applying Fabens approach to this species.

***Methods***

*Marking and Recapture*

Between 1989 and 1994, Henry Okamoto, a biologist with the state of Hawaii’s Division of Aquatic Resources, administered a mark recapture experiment for *P. filamentosus,* tagging fish throughout the main Hawaiian Islands. During this time, 4,179 juvenile and adult individuals ranging in size between 23 and 76 cm fork length were captured using hook-and-line fishing gear hauled at a rate of 2-5 feet per second. Each individual was measured to the nearest ¼ inch, surgically implanted internal anchor tag marked with a unique ID placed in the peritoneal cavity with an external monofilament streamer, and then released. 487 recaptures were recorded from 431 individuals. Individuals were outfitted with an additional tag during each recapture with two fish recaptured up to 4 times. For each individual, the location of capture (DAR statistical reporting grid), length at capture was recorded, along with the date of each recapture. Individuals recaptured by Okamoto and his team were tagged with an additional tag and all pertinent information was recorded. Local commercial and recreational fishers were made aware of the program through fliers distributed at the local fish markets, to fish dealers, fishing supply outlets and posted at small boat harbors. Fishers that caught one of these tagged fish were incentivized to report the location and depth the individual was recaptured, fork length of the individual at the time of recapture, and the date of recapture with a $10 reward for each tag returned. Recaptures of marked *P. filamentosus* were reported up to a decade after tagging with the most recent fish reported in October of 2003 (Kobayashi, Okamoto & Oishi; Okamoto, 1993).

*Fitting Growth Data*

We linearly transformed the reported fork lengths of each individual at the time of marking and recapture from inches to centimeters prior to fitting. We then removed any data from fish in the dataset that were not the of species of interest, for which no recapture was reported, or for which no tag identification number was recorded. For the remaining fish, we calculated the change in fork length (ΔL) and time at liberty, that is, the time between initial capture and marking and subsequent recapture (ΔT) for each individual. If an individual was recaptured on more than one occasion, we calculated ΔL and ΔT between the first marking event and the last recapture to avoid biasing model estimates. Fish ΔT less than 60 days or where ΔL was negative were excluded from the dataset. This process yielded 384 individuals included for further analysis.

*Parameter Estimation with Maximum Likelihood*

We obtained growth parameters by fitting this data using a maximum likelihood approach as outlined by Francis (1988) and Wang (1998). Parameters were re-estimated using different proposed error structures through minimization of the following of likelihood functions:

Constant Variance

Inverse linear relationship between expected ΔL and standard deviation

Exponentially declining residual standard deviations

Residual standard deviation as a function of Power law

A likelihood ratio test was used to select the best fit model(s). Fork lengths measured during recapture were linearly regressed against the fork lengths at recaptured predicted using Fabens’ method to compare variation between observed growth and model predictions (Should I instead just calculate the correlation between the two and call it good? If so, cor = 0.920). Finally, we regressed the length at recapture predicted by our model to von Bertalanffy parameters estimated in prior growth studies of *P. filamentosus* in the Hawaiian archipelago to determine if and how our results differed from previous studies.

*Estimating Measurement Error*

Measurement error is generally accounted for in the deviation of individual variability from the model fit. Wang’s method explicitly parameterizes individual deviation with the inclusion of an additional parameter, representing an individual’s random error term. While this can contribute some bias to the model fit, the effect is generally thought to be negligible when compared with individual variability (Wang, 1998). If we assume that measurement error can be both positive or negative, is equally likely to occur during initial capture or subsequent recapture, and that no fish experienced true negative growth, then measurement error affects only the individual’s random error term, without further bias to model estimations. Never the less, with some negative ΔL values in data, we thought it prudent to attempt to estimate the degree to which such error may have occurred. Measurement error is easy to discern from accurate measurements when it produces negative growth and impossible to determine when it produces non-negative growth. With the assumption that measurement error is equally likely to be positive or negative, we assume that ΔL values with measurement error producing negative growth correspond to a similar set of ΔL values with measurement error producing positive growth. The combined set, centered around zero, is an estimate of the measurement error for the data without accounting for an individual’s change in size during the time it is at liberty.

To account for growth while at liberty, we must assume that the individual’s length at capture or length at recapture is accurate. We then construct a set of estimated errors for all fish using the following formula:

Where is the observed length of an individual when it was recaptured and its expected length given its length at initial capture. Similarly, is the length of the individual when it was initially marked and is the expected length of the individual given its length when recaptured. Again, assuming that our measurement error is symmetrical around a mean of zero, we add a second set, equal in magnitude but opposite in sign to the first and take this to represent the distribution of measurement error though the data set. We then calculate the standard error of the measurement error.

***Results***

*Marking and Recapture*

10.5% of all *P. filamentosus* tagged were recaptured at least once (431 of 4,172 total fish). Fish that were captured one or more times were included in the dataset for further analysis. One fish was excluded from further analysis as its fork length at the time of tagging was not recorded. Seven fish were removed because the recapture date was not properly recorded. Of the remaining 431 fish recaptured, 394 were recaptured a single time, 35 fish were recaptured a total of two times, one fish was recaptured a total of 3 times and two fish were recaptured 4 times. The size distribution of fish that were recaptured ranged between 19.1 cm and 52.8 cm with a mean (+/- se) fork length of 32.8 cm (+/- 0.2). Lengths of fish at recapture ranged between 22.9 cm and 76.2 cm with mean size of 41.9 cm (+/- 0.4). The minimum time at liberty for any fish between tagging and recapture was a single day while the maximum time at liberty was 10.3 years (3,748 days). The mean time an individual was at liberty was 600 days (+/- 30).

*Fitting Growth Curve Data*

Von Bertalanffy parameter estimates, and *K,* estimated for *P. filamentosus* did not statistically differ between the two approaches (p > 0.05) (Table 1). The parameter, , fit using Wang’s method, describing individual deviation from the parameters describing the population, did not significantly differ from zero (p > 0.05). An analysis of variance between the two models further indicated that they did not significantly differ (p > 0.05). As omission of the parameter makes the two models equivalent, we carried out all remaining analysis using parameters estimated using Francis’ method. Using this method, the parameter estimate of the Brody growth coefficient was 0.24 (95% CI: 0.21 and 0.27, Bootstrap Median: 0.238) while the estimate of was 65.96 cm (95% CI: 63.15 and 69.00, Bootstrap Median: 65.91) .

The linear regression model comparing predicted FLs at recapture to observed FLs at recaptured was statistically significant (P < 0.05) with a slope (+/- se) of 0.87 (+/- 0.018) and an intercept of 5.59 (+/- 0.76). The model explained approximately 84.6% of the observed variation between observed and predicted values (Adjusted R^2 = 0.846). There was an observable trend where the predicted fork lengths of the largest individuals recaptured underestimated observed fork length values (Figure 1). This may make sense in our Linfit value being lower than some of the other studies?

../results/Predicted%20vs.%20Observed%20Lr.pdf

Figure : Comparison of observed FL at recapture and FL at recapture predicted by VBGF parameters

The set of Von Bertalanffy parameter estimates, obtained without constraint to the parameter by Ralston and Miyamoto (1983) and those produced by Andrews et. al. (2012) most closely matched our results, with both *K* and values falling within the confidence intervals estimated in this study (Table 1, Figure 2). Unsurprisingly, there was very close correlation between predicted length at recapture between the von Bertalanffy model fit with our parameters and the one fit in their respective studies (Figure 3).

../results/Figure%201.pdf

Figure 2: Comparison of length at age estimates using von Bertalanffy growth parameters from various studies for P. filamentosus in the Hawaiian archipelago

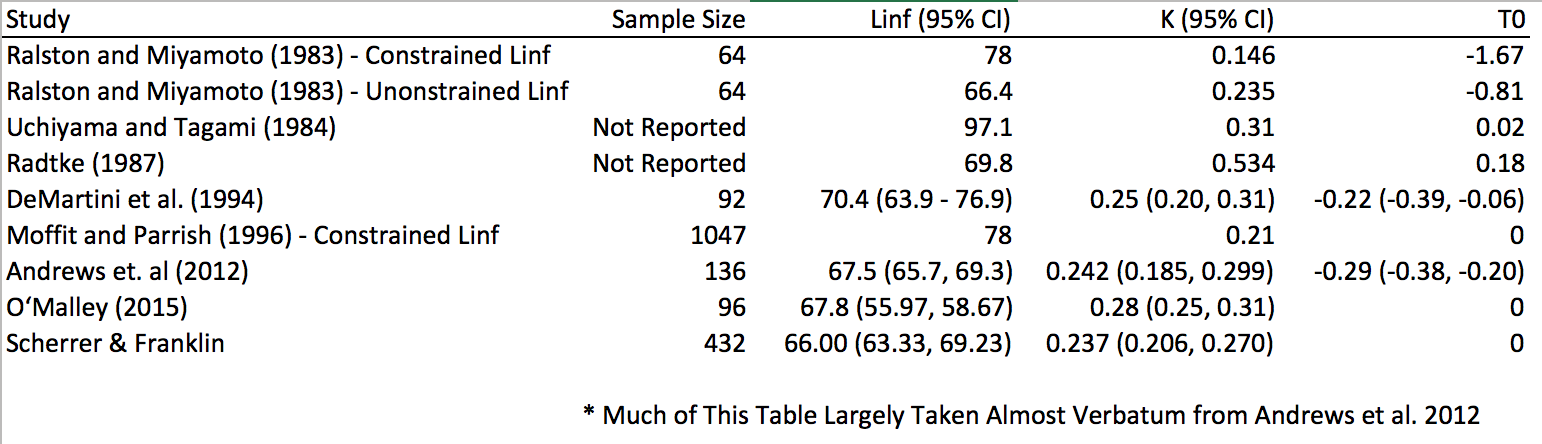


Table 1: Von Bertalanffy parameter estimates for P. filamentosus in the Hawaiian archipelago

../results/Comparision%20to%20Literature%20Estimates.pdf

Figure : Comparing predicted length at recapture using von Bertlanaffy parameter estimates from other studies of P. filamentosus across the Hawaiian archipelago

*Estimating Measurement Error*

There were 21 individuals for which negative growth was reported during their time at liberty. This is attributed to measurement error during either initial capture, recapture, or both (Oishi, 1994). Using our first method of quantifying measurement error, which does not account for growth while an individual is at liberty, we calculate the variance of the measurement error to be 1.09. Using the second method for quantifying measurement error, accounting for an individual’s growth while at liberty, we estimate a variance of 1.08 cm.

***Discussion and Conclusion***

There was strong agreement between the measured recapture lengths and those predicted using von Bertalanffy model fit using the parameters we derived using maximum likelihood approach by Francis (Figure 1). However, it appears that the growth model consistently underestimated the size of the largest fish when predicting the size at recapture. One possibility is that having obtained sufficient size, larger individuals are able to outcompete fish of smaller size classes for resources. Fitting data using maximum likelihood reduced the effect of individual measurement error on the growth model, and the central limit theorem predicts that the effect of measurement error on recorded fork length during marking or recapture is nominal. Never the less, we stress importance of accurate measurement when employing similar methodology.

Our results provide further support to studies that have used otoliths to validate individual age, through independent estimation of growth parameters, and a much larger sample size. As well, our study indicates that growth estimates from the main Hawaiian islands does not differ from those populations in the northwestern Hawaiian islands, consistent with finding of broad genetic homogeneity across the two regions (Shaklee & Samollow, 1984; Gaither et al., 2010, 2011).As the method does not rely on age estimations for estimating growth parameters, episodic deposition of otolith material does not bias results of this method. Our results are highly consistent with results derived by Andrews et al who used radio-isotopic composition to validate individual age. Our results also strongly agreed with growth estimates Ralston and Miyamoto fit without constraint to the term. In their work, they justified a constrained model based on the observation of the largest individual. In hindsight, similar to the argument presented by Francis (1988) and Sainsbury (1977), it seems problematic to constrain parameters describing a population mean based on measurements of the largest individual.

An underlying assumption when using mark-recapture methods to estimate growth is that initial capture and marking does not disrupt the growth of the individual. Estimates of individual growth between marking and recapture are highly consistent between the results of this study and those using otolith chemistry and structure to validate individual ages. Had surgical implantation of marker tags disrupted individual growth, we would anticipate recapture sizes consistently less than those predicted with growth parameters from otolith based studies. These results support for the utility of mark recapture methods applied to *P. filamentosus* for estimating growth rate parameters in other regions. However, the recapture rate in this study was slightly approximately 10%. Low recapture rates may have been the result of large population sizes, trap shy behavior of individuals following marking, or high mortality of individuals following tagging due to predation, barotrauma, or other factors of disproportionate mortality. The effort to obtain each data point is roughly ten times that required by other means, however analysis of data is substantially less involved that age validation through other means.

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